USAARL Report No. 2016-10

Pilot Cueing Synergies for Degraded Visual Environments

By Deborah Russell[1,2], Jonathan Keegan[1,3], John Ramiccio[1], Mike Henderson[1,4], David Still[1], Leonard Temme[1], Bethany Ranes[1], John Crowley[1], Arthur Estrada[1]

[1]U.S. Army Aeromedical Research Laboratory
[2]Wyle CAS Group
[3]Oak Ridge Institute for Science and Education
[4]Science Application International Corporation

United States Army Aeromedical Research Laboratory

Flight Systems Branch
Visual Protection and Performance Division
Aircrew Health and Performance Division

February 2016

Notice

Qualified Requesters

Qualified requesters may obtain copies from the Defense Technical Information Center (DTIC), Cameron Station, Alexandria, Virginia 22314. Orders will be expedited if placed through the librarian or other person designated to request documents from DTIC.

Change of Address

Organizations receiving reports from the U.S. Army Aeromedical Research Laboratory on automatic mailing lists should confirm correct address when corresponding about laboratory reports.

Disposition

Destroy this document when it is no longer needed. Do not return it to the originator.

Disclaimer

The views, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other official documentation. Citation of trade names in this report does not constitute an official Department of the Army endorsement or approval of the use of such commercial items.

The USAARL Determination Official has determined that this activity does not constitute research as defined under the human subjects protection regulations, as it is not “a systematic investigation, including research development, testing and evaluation, designed to develop or contribute to generalizable knowledge.” [32 CFR 219.102(d)].

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
19-02-2016

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Pilot Cueing Synergies for Degraded Visual Environments

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Russell, Deborah; Statz, Jonathan Keegan; Ramiccio, John;
Henderson, Mike; Still, David; Temme, Leonard;
Ranes, Bethany; Crowley, John; Estrada, Arthur

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Aeromedical Research Laboratory
P.O. Box 620577
Fort Rucker, AL 36362

8. PERFORMING ORGANIZATION REPORT NUMBER
USAARL 2016-10

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Medical Research and Materiel Command
504 Scott Street
Fort Detrick, MD 21702

10. SPONSOR/MONITOR'S ACRONYM(S)
USAMRMC

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This study evaluated existing visual symbology sets (AN/AVS7, BOSS, and FISH), haptic cues (TSAS), and aural prompting (SwiftTalker) for their compatibility, benefit, or conflict when used simultaneously in degraded visual environments (DVE). The compatibility and effectiveness of each combination of the sensed IR scene, visual symbology, and cueing were measured with quantitative measures of flight performance collected from the simulator, biometrics collected from the pilot, and the pilot's subjective reports. In general, the results indicate that test pilot flight performance was improved when using advanced visual symbologies, particularly when combined with a supplemental form of cueing (aural and/or tactile).

15. SUBJECT TERMS
Degraded Visual Environment (DVE), TSAS, Symbology, Brownout, cueing

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UNCLAS	UNCLAS	UNCLAS	SAR	90	Loraine St. Onge, PhD
					19b. TELEPHONE NUMBER *(Include area code)* 334-255-6906

Reset

This page is intentionally left blank.

Acknowledgements

The authors would like to express their sincere gratitude to the following people for their contributions to this project. Without the assistance of these people, this project would not have been successful.

- The United States Army Aviation & Missile Research, Development and Engineering Center (AMRDEC) for their patience and funding support of this project. In particular, Mr. Todd Dellert, Mr. Zoltan Szoboszlay, Mr. Ernie Moralez, and Mr. Weiliang Dai.
- Mr. Dave Durbin and Mr. Jamison Hicks for providing the SwiftTalker aural cueing software.
- Ms. Elizabeth Stokes for help with administrative matters.
- Ms. Lana Milam, Mr. Justin Dailey, Mr. Colby Matthews, and Ms. Amanda Hayes for their dedicated help with biometric measures.
- Dr. Loraine St. Onge, Ms. Catherine Davis, Ms. Amy Barrett, Ms. Jessica Cumbee, and Ms. Alexandria Austermann for their invaluable assistance with literature searches, reviews, and editing expertise.
- Mr. Rolf Beutler for his expertise in modeling and simulation and his skill integrating the necessary systems needed to perform this study.
- CPT Brandon Archer and CPT Emanuel Pierre for expertise while developing flight maneuvers.
- Mr. Paul Strickland, Mr. Charles Brown, Mr. Gary Trendowicz, and Mr. Alex Mckinney for keeping the Black Hawk simulator running around the clock and for their professionalism and expertise integrating the simulator.

This research was supported in part by an appointment to the Postgraduate Research Participation Program at the U.S. Army Aeromedical Research Laboratory administered by the Oak Ridge Institute for Science and Education through an interagency agreement between the U.S. Department of Energy and the U.S. Army Medical Research and Materiel Command.

This page is intentionally left blank.

EXECUTIVE SUMMARY

Cueing Synergy

Background

Landing maneuvers in desert conditions pose a significant risk due to the likelihood of partial or total visibility loss caused by airborne dust or sand stirred up by the helicopter's rotor downwash; this condition is termed brownout. Recent empirical evidence indicates there is a potential benefit to supplementing visual displays and symbology with tactile and aural cueing displays, thereby enhancing pilot situational awareness. How to best display and synergize this information is an open question.

Purpose

This test sought to determine optimized cueing display configurations to facilitate helicopter operations in Degraded Visual Environments (DVE). The test evaluated three visual symbology sets, as well as two non-visual cueing technologies (tactile and aural cues) for their synergy, compatibility, benefit, or conflict when used in DVE.

Methods

Eight test pilots evaluated aural and tactile cueing configurations in combination with three visual symbology sets. Four preselected flight tasks derived from the Aeronautical Design Standard Performance Specifications Handling Qualities Requirements for Military Rotorcraft (ADS-33E-PRF) were analyzed for potential beneficial or interactive effects of the cueing technologies: approach to landing, approach to hover, hover, and sidestep. The test flights were flown in the United States Army Aeromedical Research Laboratory's (USAARL) NUH-60FS research flight simulator configured with UH-60M cockpit displays with simulated infrared (IR) sensor imagery. The dust/brownout simulation was created with a dedicated image generator using purpose built software, which accurately simulates brownout conditions in the visual database (National Training Center, Fort Irwin, California). The visual symbology sets selected were a control Legacy symbology derived from the AN/AVS7 Legacy HUD (Head-up Display), the Brownout Symbology Set (BOSS) with three-dimensional (3D) conformal symbology, and the Forward-Looking Integrated Systems for Helicopter (FISH) symbology. Cueing effectiveness was assessed by recording objective indices of flight performance, objective biometric measures, and subjective ratings and comments by the test pilots. The formal subjective rating tools included the Bedford Workload Scale, Cooper-Harper Handling Qualities Rating Scale, Visual Cue Index (VCI), a demographic and cueing display ranking questionnaire, and free-flow comments report.

Conclusions

1. Generally, pilots performed better using advanced visual symbologies (BOSS and/or FISH) when combined with a supplemental form of cueing (aural and/or tactile).
2. Test pilots' preferred supplemental cueing modality was dependent on the type of visual symbology and/or flight maneuver.
3. Research pilots observed a greater number of pilot- induced oscillations during the hover and sidestep maneuvers when aural cueing was paired with either Legacy or FISH visual symbologies.

4. Overall, subjective and flight performance measures indicated that the BOSS symbology was the preferred visual symbology set, although some attributes of FISH were preferred when performing the sidestep maneuver.
5. Pilots preferred aural cues that provided situational information over aural cues that demanded corrective action to satisfy a required performance measure.
6. In general, test pilots preferred the TSAS cueing display over the aural cueing display.
7. Biometric measures of stress were associated with performance trends on selected flight maneuvers. Future studies should exploit these measures as objective correlates of aviator performance.

Table of contents

Introduction 1
Background and significance 1
Visual cues 1
Synthetic vision (sensed and/or database imagery) 2
Visual symbologys sets (Legacy HUD [AN/AVS-7], BOSS, and FISH) 3
Supplemental cueing 4
Aural 4
Tactile 5
Multisensory approach... 7
Study rationale and expectations... 8
Study metrics 8
Deliverables 8
Method/test procedures 9
Test equipment 9
Flight simulator.. 9
Imagery/Cue display 9
Instrumentation of evaluation pilots 9
Flight tasks and standards... 9
Biological metrics 10
Qualitative subjective metrics.. 11
Test conditions.. 11
Test order 11

Table of contents (continued)

Simulator time requirements 12

Evaluation pilots 13

Results 14

Approach to landing 14

Flight performance 14

Subjective data 20

Questionnaire rank data 21

Approach to landing results summary 22

Approach to hover 22

Flight performance 22

Subjective data 27

Approach to hover summary 27

Hover 28

Flight performance 28

Questionnaire rank data 30

Subjective data 30

Hover summary 31

Sidestep 31

Flight performance 31

Questionnaire rank data 34

Subjective ratings 35

Sidestep summary 35

Table of contents (continued)

Biometric data ... 36

Condition-specific effects for each significant biometric outcome variable ... 37

Discussion ... 38

Approach to landing ... 38

Approach to hover ... 39

Hover ... 40

Sidestep ... 41

Conclusions ... 42

Limitations and recommendations ... 43

References ... 46

Appendix A: Flight performance and subjective results ... 51

Appendix B: Questionnaire ... 62

Appendix C: Outlier Charts ... 64

Appendix D: Biometric results ... 75

List of figures

1. Analog (left) and digital (right) cockpits ... 2
2. Position index data by symbology (left) and position at touchdown data for BOSS ... 16
3. Heading index data by symbology (left) and the SD of heading during the level ... 17
4. Altitude index data by symbology. ... 18
5. Speed index data by symbology (left) and the RMSD of speed during the level ... 19
6. Longitudinal speed at touchdown data (left) and lateral speed at touchdown data (right) ... 20
7. Position index data by symbology (left) and the RMSD of the longitudinal position ... 24

Table of contents (continued)

List of figures

8. The SD of heading data during the level segment for FISH (left) and during the 25

9. Altitude index data by symbology (left), altitude RMSD for level and hover segments (middle and right). 26

10. Speed index data by symbology (left), speed RMSD for level and approach segments (middle and right). 26

11. Position index data grouped by symbology. 28

12. Heading index data grouped by symbology (left) and the RMSD of heading (right). 29

13. Altitude index data by symbology. 30

14. Position index data grouped by symbology (left) and the RMSD of lateral position 32

15. The RMSD of heading for FISH and grouped by cueing. 33

16. The maximum lateral velocity data for the Legacy symbology grouped by 34

17. Sum of pilots' rank scores for Approach to Landing. 39

18. Sum of pilots' rank scores for hover. 41

19. Sum of pilots' rank scores for sidestep. 42

List of tables

1. Flight tasks derived from ADS-33. 9

2. Symbology/cueing combinations numbering system. 12

3. Pseudo-Randomized test order of symbology combinations 12

4. Mean deviations by symbology and significance values between symbologies. 14

5. Cueing mean deviations and significance values for Approach to Landing. 15

6. Summary of subjective data comparing symbology sets. 21

7. Summary of subjective test data where significance was found between cueing 21

Table of contents (continued)

List of tables

8. Cumulative summation of ranking from questionnaires.. 21

9. Approach to Landing summary. 22

10. Mean deviations by symbology and significance values between symbologies. 22

11. Cueing mean deviations and significance values for Approach to Hover. 23

12. Summary of subjective data. 27

13. Summary of symbology sets and cueing displays for Approach to Hover. 27

14. Mean deviations by symbology and significance values between symbologies. 28

15. Cueing mean deviations and significance values for Hover. 28

16. Summations of rankings from questionnaires... 30

17. Summary of subjective data for Hover. 31

18. Summary of symbology sets and cueing displays for the Hover maneuver. 31

19. Mean deviations by symbology and significance values between symbology sets. 31

20. Cueing mean deviations and significance values for sidestep. 32

21. Summations of rankings from questionnaires... 34

22. Summary of subjective data comparing symbology sets. 35

23. Summary of subjective test data where significance was found between cueing.................. 35

24. Summary of symbology sets and cueing displays. 35

25. Summary of conditions with the lowest biometric stress responses by maneuver and 36

This page is intentionally left blank.

Introduction

Background and significance

Flying in blowing sand, dust, rain, or snow is currently a major problem for the U.S. military, costing over $100 million a year in aircraft losses and resulting in the loss of over 600 lives from 2002 to 2012 (Whittle, 2012). Degraded visual environment (DVE) is the term used to describe the condition when visibility outside the aircraft is severely degraded or nonexistent. Of primary concern is brownout, which occurs when the visual environment is obscured by recirculated dust, dirt, or sand due to rotor downwash as a helicopter takes off, hovers, or lands. A similar phenomenon occurs in snow and is called whiteout (NATO Task Group HFM-162, 2012). In order to successfully operate in DVE, pilots must be able to detect and perceive drift, height above terrain, descent rate, ground speed, attitude, ground slope, terrain features, landing point location, obstacle clearance, and moving obstacles (NATO Task Group HFM-162, 2012).

Current instrumentation suffers from two major limitations. First, available displays do not contain sufficient information, i.e., drift, ground slope, terrain features, landing point location, obstacle clearance, and moving obstacle detection. Second, information bandwidth is insufficient to communicate the necessary information in a timely manner. During an approach to landing in a normal visual environment, the pilot will rely on outside visual references for information regarding ground speed, lateral drift, landing point location, and the landing zone environment. However, once the pilot enters DVE, he can no longer access those outside visual cues. Switching to flight instruments does not solve the problem because they do not provide these key parameters. Thus, the lack of necessary information in DVE increases the pilot's risk of crashing due to unrecognized excessive descent rates, unintended drift, and ground obstacle collisions (Colucci, 2007).

Strategies being urgently explored to provide the necessary information needed to operate during DVE include virtual reality, infrared imagery, advanced visual symbology, tactile cues, and aural cues. Logically, an intuitive multisensory approach may provide the information necessary for DVE operations. This report explored the efficacy of combining visual, tactile, and aural displays to increase information bandwidth while avoiding sensory conflict.

Visual cues

During landing, visual references from the outside environment are a pilot's primary source of information (NATO Task Group HFM-162, 2012). Visual cues from the outside world during landing provide pilots with information regarding aircraft attitude and the landing zone environment; once a pilot enters DVE, he/she is literally working in the blind. Because humans are primarily visual creatures, it is understandable that visual displays would become the primary DVE mitigation instrument (Curtis, Jentsch, and Wise, 2010) acting as the pilot's window to the world (Stokes and Wickens, 1988). Visual displays can be analog or digital (figure 1). Traditional analog displays used simple symbology, such as the use of colors (red, yellow, green) to indicate safe operating ranges and performance limitations. As analog displays were replaced with digital (glass) displays, symbology became more complex in an effort to provide pilots with more accurate information. Digital displays are used to relay flight data (airspeed, altitude, attitude, vertical speed, and heading), navigational data, aircraft systems data, weather, and a variety of additional information needed to complete complex missions to the pilot. Glass cockpit displays have made it possible to provide pilots with information in intuitive formats when it is needed (Mejdal, McCauley, & Beringer, 2001).

Figure 1. Analog (left) and digital (right) cockpits.

Synthetic vision (sensed and/or database Imagery)

Pilots rely on focal vision for object recognition relative to the helicopter location. Ambient, or peripheral, vision provides information relating to the helicopter's position, motion, and attitude. Loss of focal vision information in DVE can be overcome with synthetic vision systems. Forward-looking Infrared (FLIR) displays and database imagery are two synthetic vision systems available to pilots.

FLIR

FLIR refers to a forward-looking infrared sensor mounted on the aircraft that provides pilots with a view of the external world even when operating at night or in obscured environments. This capability provides pilots with cues that traditional instruments cannot provide, such as drift, ground slope, terrain features, obstacle clearance, and landing point location. Having an image of the external visual environment provides pilots with pertinent information necessary for safe operations in DVE; however, FLIR imagery has its limitations. The quality of the FLIR image can be distorted due to sensor restrictions. Very fine dust particles can obscure the sensors and prevent them from detecting objects. FLIR imagery relies on differences in heat to detect objects and produce images. While useful, FLIR imagery is not infallible—rain-soaked terrain on a cloudy day may present little thermal contrast. Also, depending on the climate, twice a day objects are likely to have very small heat differences making object detection difficult and FLIR imagery less useful; this phenomenon is known as thermal crossover.

The FLIR image displays can also affect the quality of the picture. Time delays caused by latency and refresh rate can provide pilots with inadequate information. Additionally, size-distance perception can be affected by changes in the field of view. As the field of view increases, the external objects are minified on the display making the objects appear further away. FLIR images can be displayed on head-up displays (HUDs)s or panel-mounted displays

(PMDs). Panel-mounted displays require pilots to reacquire a scan as their eyes move from inside the cockpit to the external environment.

For the purpose of this study, it was determined that a PMD with real time FLIR imagery would be paired with the various visual symbology sets. Henceforth, any reference to infrared (IR) or IR scene refers to a symbology set over the simulated IR sensor imagery. The display presents a sensor's 60° field-of-view. In addition to the IR imaging, advanced symbology has been developed to overlay the IR image to provide pilots with meaningful cues and information required for landing. Symbology provides an artificial representation of real world information and can serve to enhance displays (Curtis, Jentsch, and Wise, 2010). Properly designed visual displays with advanced symbology over IR images are intended to provide pilots with increased situation awareness during DVE. However, excessive use of symbology and the use of undistinguishable symbols can lead to clutter and confusion, which can negatively affect performance.

Visual symbology sets (Legacy HUD [AN/AVS-7], BOSS, and FISH)

The Federal Aviation Administration (FAA) requires an altimeter, airspeed indicator, and magnetic compass instruments for reference during visual flight rules (VFR) flights. This indicates that even with good visibility and a discernable horizon, pilots cannot accurately gauge airspeed, altitude, or heading without the aid of flight instruments. Additionally, symbology provides pilots with redundant visual cues.

This project focused on three visual symbology systems: the control symbology (Legacy HUD), Brownout Symbology Set (BOSS) with 3-dimensional (3D) conformal symbols, and Forward-Looking Integrated Systems for Helicopters (FISH). For evaluation, each of these visual symbology systems was overlaid on an IR image on a Head-Down Display (HDD). A basic overview of each system follows.

Legacy

The Legacy HUD symbology is the baseline control display system currently used in many U.S. Army helicopters. The system's cues include attitude, heading, waypoint bearing and distance, altitude, performance, and velocity vector. The system was designed for use in conjunction with a HUD system; however, it may also be used with an IR scene HDD.

BOSS

The BOSS provides "visual quality" landing capabilities in zero visibility, and horizontal and vertical speed guidance to the landing zone (Thompson, 2011). BOSS utilizes 3D conformal symbols, which allow a 3D view of the landing zone added to the two-dimensional (2D) symbology set. Conformal symbology facilitates the mental integration of information outside the helicopter and the symbology presented on the display (Wickens, 2003). BOSS was developed using symbology tailored for rotorcraft during brownout conditions and presents critical flight information necessary for safe takeoffs, hovers, and landings in DVE. A 2009 study of BOSS showed that pilots were able to effectively use the symbology to land helicopters in brownout conditions; however, the system did not indicate lateral drift at a level considered to be suitable for safe DVE operations (Szoboszlay, Turpin, and McKinley).

FISH

FISH uses pictorial pursuit guidance symbology enroute, and prior to landing switches to forward-looking landing guidance symbology. FISH symbology maintains a forward looking perspective, which is consistent with how pilots naturally fly when in visual flight conditions. FISH attempts to reduce visual search times by integrating all cues in the center of the screen. Clutter is also reduced as the system switches from an *Enroute page* to *Hover page* format prior to landing. The display also possesses the ability to reroute the trajectory in-flight, which might be needed due to unforeseen events such as obstacles, traffic, or an unexpected change in the direction of approach to the landing site. In both simulator and in-flight testing of FISH, pilots were able to achieve improved tracking performance, fewer missed waypoints, and lower workload (Moralez et al., 2011).

Visual display limitations

Most information is presented visually in modern cockpits; thus, the visual channel can become overloaded while operating in high-workload conditions such as DVE (Veltman, Oving, and Bronkhorst, 2009). Overreliance on any one sensory channel, especially during periods of high workload, can cause cognitive tunneling and sensory bottleneck (Allan et al., 2010). Visual channels are often overburdened by cluttered visual displays and complex symbology, rendering pilots susceptible to cognitive tunneling. Cognitive tunneling is a phenomenon of focusing so intently on a display that the pilot loses focus of the environment as a whole. As more visual attention is required, the visual sense may become overloaded and critical information may be missed or misinterpreted (Mateo et al., 2012). There is also a temporal cost to cluttered visual displays: Displays can distract or slow down the pilot from obtaining necessary information. Longer search times can negatively impact performance and increase workload (Curtis, Jentsch, and Wise, 2010). Sensory overload associated with congested displays and complex symbology can actually cause pilots to see and comprehend less as more information is provided.

Supplemental cueing

<u>Aural</u>

In DVE, aural alerts can be beneficial by alerting pilots of unintended aircraft orientations and by providing pilots with navigational reference data, i.e., in the form of altitude callouts. Aural alerts are most effective for simple short messages that call for immediate action (Sanders and McCormick, 1993). Auditory cues possess several characteristics that can make them preferable to visual cues, particularly when visual channels are already overloaded. Specifically, auditory cues have the ability to capture a pilot's attention and elicit an urgent response regardless of head position or eye fixation (Dehais et al., 2014; Vidulick, Wickens, Tsang, and Flach, 2010). They are especially useful when operating in close proximity to the ground where unintentional drift, changes in altitude, and sink rates require immediate corrective action to prevent a potentially serious accident. Aural alerts can be speech or nonspeech (tones/earcons) (Kenny and Wei, 2009). Earcons are a form of nonspeech notifications composed of beeps and other distinctive sounds that signal distinct events and are used extensively in computer interfaces. Nonspeech cues such as earcons have potential advantages over speech in their ability to grab attention and be concise, specific, and distinctive. However, their meaning must be learned and retained. The presentation of the aural alerts can range from monaural to 3D audio. The more technically challenging 3D audio format allows aural alerts to be localized to a specific location in space.

Aural cues design considerations

Effective aural displays rely on timely and accurate interpretation of aural alerts. Overuse of audio displays can lead to auditory clutter of competing displays and increase the risk for auditory masking (Curtis, Jentsch, and Wise, 2010). In addition to being masked, research has shown that during periods of high workload, auditory signals are often missed. For example, air safety reports show that a significant number of accidents are caused by lack of reaction to auditory alarms due to inattentional deafness, a phenomenon that occurs when high perceptual load tasks consume attentional capacity to the point where task-irrelevant information cannot be processed (Dehais et al). Auditory displays can also be intrusive and distracting. To overcome these limitations, certain design guidelines should be followed. In general, signals should be discernable, consistent, and not provide more information than necessary. Presentation of audio signals should avoid extremes of auditory dimensions, establish intensity relative to ambient noise, and not overload the auditory channel. Aural cues, while suitable for grabbing attention, are not recommended for long, complex messages containing information that will need to be recalled at a later time.

The initial aural cues are designed to emulate an easily fielded system that has already been approved for flight use. To this end, this study utilized the SwiftTalker voice audio symbology system to monaurally alert pilots of altitude and unintentional drifts. Subsequent studies will incorporate more complex aural cues (e.g., 3D, earcons). SwiftTalker verbal alerts are provided through aircrew helmets. SwiftTalker uses Text-to-Speech (TTS) technology to create the verbal alerts. These alerts are easy to manipulate, nonreliant on human participation, have a low lifecycle cost, and have rapid prototype-delivery phases and iterations. In this study, SwiftTalker provided pilots with altitude alerts during approach to hover, verbally announcing “250 FEET,” “40 FEET,” “30 FEET,” “20 FEET,” and “10 FEET.” Altitude alerts were linked to the radar altimeter to ensure accurate feedback was provided to the pilots. Drift detection occurred during the 30 foot (ft.) hover condition and the alerts were via verbal cueing. If a lateral drift was detected, the system announced “DRIFTING LEFT” or “DRIFTING RIGHT,” while longitudinal drifts were announced as “DRIFTING FORWARD” or “DRIFTING AFT.” Additional cues alerted pilots when to accept approach guidance via the voice command “Assume Guidance” or notified pilots if their heading or airspeed did not match desired parameters via the voice commands “Check Heading” and “Check Speed.” SwiftTalker cues provided pilots with altitude information that was redundant with all symbology sets.

Tactile

As visual and aural channels have become overwhelmed in the cockpit, there is new interest in utilizing the sense of touch with tactile cues (Lu et al., 2011). A primary reason for utilizing tactile displays is that their use results in minimal interference with visual and aural channels. This is largely because they share few competing attentional resources. Thus, tactile cues can be used to unburden overtaxed visual and aural modalities and increase overall sensory processing bandwidth. The increase in bandwidth means greater attentional capture and quicker response times for information that would otherwise be delayed or missed (Jones and Sarter, 2008). Experience has shown that tactile cues are useful in providing spatial orientation and guidance information, notifications and alerts, and flight-control feedback (Allan, et al., 2010). Tactile cues are especially useful in demanding and distracting environments and in some cases they have outperformed visual displays under conditions of high cognitive and visual workload (Elliott, Schmeisser, and Redden, 2011).

Tactile displays usually convey information using vibrations or force. In the cockpit, tactile cues can be integrated in the flight controls or may be delivered through a vest, belt, and/or seat apparatus. In practice, arrays of electromagnetic vibro-tactile stimulators called tactors are used to create the tactile display (Lawson and Rupert, 2014). Currently, tactors cue pilots via a unique tapping sensation on the shoulders, around the waist, and in the seat cushion (Cox, 2014). For example, directional flight deviations can be cued on a corresponding belt location, with an unintended drift to the right being cued on the right side of the belt and the rate of deviation signaled by tactor firing frequency rate. Systems utilizing this encoding scheme have demonstrated improved system awareness and heightened situational awareness. Key design considerations include the tactor size and strength, user comfort, ease of donning, and anthropomorphic considerations (bulk, egress, wearability, and flight gear compatibility).

Tactile system selection

Tactile cueing was selected based on its potential ability to aid pilots operating in DVE; specifically, tactile cueing was used to provide redundant drift, course, and altitude information. The tasks pilots performed (approach to landing, approach to hover, hover, and sidestep) were selected because the test a pilot's ability to enter and operate in DVE conditions. Additionally, it was necessary that the tactile display ensemble be comfortable, compatible with aircraft operation, and allowed for emergency egress. Finally, the tactile display system's software and hardware was integrated into USAARL's NUH-60FS.

The Tactile Situation Awareness System (TSAS) was found to meet all selection requirements. Specifically, it used noncontinuous tactor stimulation to preclude sensory habituation, met airworthiness requirements, and was compatible with the NUH-60 simulator software requirements. In flight tests, TSAS was shown to be capable of providing altitude, attitude, velocity, navigation, acceleration, threat location, and target location data (McGrath et al., 2004). Additionally, TSAS has shown to be effective at reducing tracking errors and improving situational awareness during landings in both degraded and good visual environments (Craig et al., 2008). Further, Kelley, Grandizio, Estrada, and Crowley (2014) found that aviator performance with vibro-tactile displays was not adversely affected by adaptation or habituation following 12 continuous hours of simulated flight. The TSAS system selected and used in this experiment consisted of eight tactors along the belt that correspond to direction of drift or course deviation. Shoulder and seat tactors reported altitude deviations. On course forward flight was cued via the center tactor.

Multisensory approach

Flying in DVE presents pilots with the potential for high workload and sensory overload. Single modality solutions can increase the already high workload and provide an incomplete picture of the outside world, resulting in a negative effect on performance. Sensory overload and increased workload can lead to missed cues, loss of situation awareness (SA), and adversely affect overall safety. To overcome the risks associated with DVE, effective and efficient use of pilot resources are required. In recent years, interest in multimodal interfaces has increased for complex, event-driven domains that are at risk for sensory overload due to an overreliance of visual displays (Sarter, 2007). Wickens' Multiple Resource Theory (MRT) predicts that performance can be improved by distributing information across sensory channels.

According to MRT, humans are capable of processing information from multiple sensory sources in parallel. Thus, pilots are capable of processing visual, sound, and tactile inputs simultaneously using multiple sensory resources (Vidulick, Wickens, Tsang, and Flach, 2010). Tasks using compatible resources that allow parallel processing may usually be performed simultaneously. Multimodal systems support time-sharing and attention management. Based on MRT, a multimodal approach that utilizes visual, audio, and tactile senses may provide pilots with the information required for safe DVE operations and prevent overreliance on the visual sense. Many bimodal research studies in which auditory and tactile cues have been introduced to provide directional and navigational guidance have supported this theory. A meta-analysis of more than 600 studies investigated the effectiveness of tactile cues versus visual cues versus visual-tactile cues and found that a multisensory approach using complementary visual and tactile cues increased performance for orientation, task information, and alerts (Elliott et al., 2009). Research conducted by Sklar and Sarter (1999) investigated response times for uncommanded changes of an automatic flight deck system using tactile, visual, and tactile-visual cueing. It was found that response times for tactile and tactile-visual conditions were significantly better than response times for a visual only condition, demonstrating the advantage to bimodal presentations. Research that explored the efficacy of audio-tactile systems found that well-designed audio-tactile displays have the potential to result in more resilient systems that enable the operator to receive the necessary information, even when one modality is compromised (Mateo et al., 2012).

Possible limitations to multimodal approaches

While there is great promise with a multisensory approach to solving the DVE problem, it is important to consider certain limitations of the multimodal approach. Moving from uni- or bi- to multimodal displays involves certain tradeoffs. Multimodal systems may aid in time-sharing, but there is also a potential increase in interface management and monitoring demands. Due to limited capabilities in regard to human information processing, multisensory cueing could overload the pilots' cognitive abilities, resulting in increased workload and missed cues.

An additional cautionary note to consider is The Principle of Inverse Effectiveness in Multisensory Integration which states:

> As the strength of multisensory integration responses increase, the strength of responsiveness to individual sensory stimuli decreases. Consequently, multisensory cueing indices will naturally serve to improve associated performance when compared to individual stimuli. This improved degree of performance may be illusory to a certain degree, merely by the nature of the multisensory inputs *(Holmes, 2009)*.

Studies are needed to determine if tactile, audio, and visual cues are effective at directing pilots in DVE and to establish which modes are most effective in delivering certain types of information. Another consideration which should be addressed is whether audio and tactile cues should merely provide pilots with redundancy for missed visual cues or if they should provide additional information that visual displays are not capable of effectively providing.

Study rationale and expectations

There is a multitude of research exploring bimodal systems, but trimodal systems using visual, aural, and tactile cueing research is limited. It was the goal of this study to determine: 1) if combining symbology/cueing sets would improve flight performance and/or reduce workload/stress, 2) if the effectiveness of different combinations of the symbology/cueing sets would be reflected in their subjective evaluations, observed flight performance, and pilot workload/stress, and 3) if the effectiveness of different combinations of symbology/cueing sets would vary with the flight task.

Study metrics

The compatibility and effectiveness of each combination of the sensed IR scene, visual symbology, and sensory cueing were assessed with quantitative measures of flight performance collected from the simulator, biometrics collected from the pilot, and the pilot's subjective reports. Symbology set effectiveness was evaluated three ways: 1) the flight performance enabled, 2) the degree of workload and stress induced, and 3) the evaluation pilots' assessments evoked. Simulator data documented the symbology sets' effect on flight performance. Biometrics (i.e., heart rate variability, respiratory rate, and galvanic skin response) were collected as measures of the symbology sets' effect on workload and stress. Cooper-Harper, Bedford Workload Scale, and Visual Cue Index (VCI) data along with free reports documented the evaluation pilots' assessments of the symbology/cueing sets' utility.

Deliverables

The deliverables of this effort were to:

1. Determine the relative efficacy of the specified visual symbologies when teamed with tactile and aural cues;
2. Evaluate the effect of these multiple simultaneous cueing technologies and their effect on flight performance, biometrics, workload, and situational awareness; and
3. Provide recommendations for managing the integration of these advanced cueing technologies.

Method/Test procedures

Test equipment

Flight simulator

All testing was conducted using USAARL's NUH-60FS research flight simulator.

Imagery/Cue display

IR scene and symbology information was shown on the primary flight display of the UH-60M instrument panel emulation. Tactile cues were presented via TSAS belt, shoulder harness, and seat cushion tactors. Audio cues were presented via speakers inside HGU-56/P rotary-wing aircrew helmets. The windscreen and chin bubble exterior views were clouded with realistic dust and obscured to match the aircraft integration test configuration currently utilized by Aeroflightdynamics Directorate, National Aeronautics and Space Administration (NASA)-Ames Research Center.

Instrumentation of evaluation pilots

The test instrumentation used by the evaluation pilots included: HGU-56/P rotary-wing aircrew helmets; TSAS tactor belt, shoulder harness, and seat cushion; and biometric instrumentation consisting of three electrocardiogram (ECG) electrodes, two galvanic skin response (GSR) electrodes, a chest strap respiration transducer, and BioNomadix® wireless transmitter.

Flight tasks and standards

The sponsor requested that the display be evaluated with flight tasks derived from ADS-33. Table 1 lists the four derived flight tasks selected. The flight tasks were flown in the order presented for each symbology/cueing combination.

Table 1.
Flight tasks derived from ADS-33.

Flight Task Order	
First	Approach/Landing
Second	Approach/Hover
Third	Hover
Fourth	Sidestep

Approach to landing

This task started with the aircraft 250 ft. above ground level (AGL) moving at 80 knots toward the landing point 1.5 nautical miles (NM) away. Descent from 250 ft. AGL began 0.8 NM from the landing point. The pilots approached the landing point in a straight line and touched down with 1.5 to 2 knots ground speed and minimal hover. Metrics for this task included deviations from an ideal approach path, touchdown speed, touchdown heading, and touchdown location.

Approach to hover

This task started with the aircraft 250 ft. AGL moving at 80 knots toward the landing point 1.5 NM away. Descent from 250 ft. AGL started 0.8 NM from the hover point. The pilots approached the hover point in a straight line and established a 30 ft. AGL hover. Metrics for this task included deviations from an ideal approach path and hover quality (heading, altitude, and position).

Hover

This task required the maintenance of a 30 ft. AGL hover for 2 min. Metrics for this task included deviations from an ideal hover quality (heading, altitude, and position).

Sidestep

From a hover, the pilot rapidly relocated the aircraft using a sidestep maneuver and returned to a stable hover above a predesignated spot. Metrics included maximum lateral velocity, altitude maintenance, heading maintenance, relocation accuracy, and 20 s pre- and 20 s post-hover quality (heading, altitude, and position). Crashes, loss of control, missed approaches, and/or aborted landings were reported separately.

Biological metrics

The projected effect of the flight instrumentation on perceived workload utilized three biometric measures: heart rate variability (HRV), galvanic skin response (GSR), and respiratory rate (RR). These measures were selected for their responsiveness to workload, minimal invasiveness, compatibility with the testing paradigm, tolerance of the simulator environment, and potential utilization in aircraft. The biometric data were synchronously collected with BIOPAC's BioNomadix® and BHAPI instrumentation/software. This instrumentation, like the biometric measures, was selected for its tolerance of the simulator testing environment and potential utilization in aircraft. Each specific biometric data array were analyzed with BIOPAC's AcqKnowledge® and MathWorks'® MATLAB® software.

HRV has been used successfully to observe quick or minute shifts in documented workload (interpreted in the current study as stress) that have eluded simpler measures of heart rate. HRV data capture requires high resolution ECG instrumentation that reports detailed heart activity data (specifically the R-R interval). The selected high resolution (500+ Hertz) ECG instrumentation was easily worn, and reported wirelessly as part of the BioNomadix® system (although applied successfully in the NUH-60FS simulator, any planned or anticipated use of this instrumentation in the UH-60 aircraft would require an approved Airworthiness Certification).

GSR has proven effective at discerning cognitive workload changes in naval simulator studies and demonstrated greater sensitivity to shifts in workload than traditional subjective or subject-reported measures. GSR, also commonly referred to as skin conductance or electrodermal activity, involves the measure of electric conductivity alterations caused by the skin's ionic sweat production. The means of collecting this information is noninvasive; the selected equipment is compact, created little or no discomfort to the test pilots, and reported wirelessly. Through the BIOPAC® hardware, GSR was integrated into the multichannel ECG array utilized for HRV data collection.

RR has been used successfully as a measure of cognitive workload and stress in the literature, including multitasking driving simulator research, which suggested appropriateness for flight simulator studies (ignoring any possible 6 degrees of freedom initiated variability). Respiratory rate describes the rate of breathing, and in some cases can also include the volume of a test pilot's inhalation via measured lung expansion. Respiratory rate data can be either extracted from high-resolution ECG data or independently collected through a respiration transducer. While the independent RR collection method requires a chest strap, it was selected because of its increased signal-to-noise ratio, which allowed for a wider array of analysis (e.g., inclusion of breath volume as opposed to simple breathing rate data). Through the BIOPAC® hardware, RR was integrated into the multichannel ECG array utilized for heart rate variability and GSR data collection.

Qualitative subjective metrics

Following completion of each scored symbology set combination test run, pilot subjective impressions were captured using the Cooper-Harper Handling Qualities Rating Scale, Bedford Workload Scale, and VCI ratings. The Visual Cue paradigm was used to rate aural and tactile cues in addition to visual symbology. After test pilots finished all flight combinations, they were asked to complete a questionnaire, ranking cueing displays from easiest to fly - to most difficult, for each symbology set. The questionnaire also captured flight experience and free report sections. During the testing, research pilots collected test pilot free flow comments.

Test conditions

Test flights were flown with a single unassisted (minimal crew coordination) evaluation pilot at the controls with wind and turbulence turned off. The out-the-window views, including the chin bubbles, were obscured with blowing sand and dust below 100 feet AGL for all flights. The IR scene imagery within the display was unobscured.

Test order

Training and testing required two days for each of the eight evaluation pilots. The first day began with a safety brief, description of the study's purpose and instrumentation, and six simulator flight hours of symbology socialization/training. On the second day, test runs (each run is composed of the four selected flight tasks: approach to landing, approach to hover, hover, and sidestep) were flown. Three consecutive test runs were flown for each of the 12 symbology/cueing combinations shown in table 2. The first two runs provided additional training and preparation for the third run, which was for score. Thus, on the second day, each pilot practiced each of the 12 symbology combinations listed in table 2 twice and then once for score, for a total of 36 runs, 12 of which were scored runs. In turn, each of these 12 scored runs provided 4 data sets: approach to landing, approach to hover, hover, and sidestep. Thus, 48 data sets were harvested from each of the eight evaluation pilots. The pseudorandom testing sequence is shown in table 3.

Table 2.
Symbology/cueing combinations numbering system.

Visual Symbology Set	**IR Scene**	**IR Scene + Tactile**	**IR Scene + Aural**	**IR Scene + Tactile + Aural**
Legacy	1	2	3	4
BOSS + 3D Conformal	5	6	7	8
FISH	9	10	11	12

Table 3.
Pseudorandomized test order of symbology combinations.

	Test pilot							
Runs	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1, 2, 3	3	8	12	2	7	8	10	1
4, 5, 6	4	12	3	3	11	2	6	9
7, 8, 9	8	4	6	12	3	10	1	12
10, 11, 12	1	3	11	9	9	4	12	5
13, 14, 15	5	7	5	8	5	1	9	10
16, 17, 18	10	1	1	11	8	7	8	8
19, 20, 21	7	5	2	10	1	12	4	11
22, 23, 24	2	11	8	4	10	3	3	7
25, 26, 27	9	2	10	6	6	11	5	2
28, 29, 30	11	9	4	1	12	5	7	4
31, 32, 33	6	6	7	5	4	9	11	6
34, 35, 36	12	10	9	7	2	6	2	3

As seen in table 3, the pseudorandomized order of the symbology/cueing combinations (from table 2) was specified. For example, test pilot 3's fourth, fifth, and sixth runs were test symbology combination no. 3 (circled). As shown in table 2, symbology combination no. 3 utilizes aural cues and has the IR scene overlaid with AN/AVS-7 Legacy HUD symbology.

Simulator time requirements

The study was designed to enable a pilot to complete data collection in 2 days. The first day was dedicated to socialization of the visual symbology, tactile cues, and aural cues and took roughly 6 hours per pilot. The second day was dedicated to the test runs. Each pilot flew 6.6 hours of flight time (roughly 11 minutes for each of the 36 test runs).

Evaluation pilots

The test plan was specifically designed to provide a structured environment to capture expert pilot flight performance and subjective assessments of display, symbology, and cueing characteristics. Accordingly, the sponsor selected the eight formally trained and rated rotary-wing pilots who served as the evaluation pilots. The evaluation pilots had sufficient flight experience to enable them to provide expert guidance in the establishment of display requirements. The evaluation pilots performed the flight tasks and provided subjective estimations of workload and cue utility, biometric measures of workload and stress, and objective measures of their flight performance. Demographics of the evaluation pilots' flight experiences were collected with a questionnaire.

Analysis

Flight performance data were evaluated for pilot performance for approach to landing, approach to hover, hover, and sidestep maneuvers. Data were captured on the third run for each condition. Repeated measures Analysis of Variance (ANOVA) was performed on position, altitude, heading, and speed measures. A logarithmic transformation of the data was performed to pass the Shapiro-Wilks test for normality required of most performance-specific statistical testing. Means were reported using raw data, while statistical significance was derived from log-transformed data. A p value less than .05 was used for statistical significance. Flight performance data were grouped by maneuver and displayed as a column graph. Performance measure indices are grouped by symbology. Each symbology bar is the average of all four combinations of cueing displays (IR, TSAS, Aural, TSAS and Aural). Cueing graphs display results for a specific performance measure used to compute the performance index within a specific symbology set. Only charts and data with statistically significant findings are presented. Tables showing both statistically significant and non-significant results are located in appendix a.

Subjective reports include results by maneuver for Cooper-Harper, Bedford Workload Scale, and VCI ratings. Friedman Tests were performed on the subjective results to test for differences between the 12 conditions. Further investigations with a Wilcoxon Sign Rank test were performed between visual symbologies and cueing conditions.

Pilot questionnaire data (appendix b), which required pilot assessment of cueing within symbologies, were then examined and presented as rank data. Raw data are represented to indicate pilot preference. Due to the confusing nature of the original questionnaire given to pilots 1 and 2, a revised questionnaire was used for rank data and only the data from pilots 3 through 8 were analyzed. Finally, pilot biometric data analysis includes summaries for both condition and maneuver. In the following sections, data for each task are presented graphically and evaluated statistically.

Results

Approach to landing

To determine the optimized cueing display configurations used to facilitate helicopter approach to landing in DVE, all combinations of cueing were recorded and analyzed. Result tables are provided for both symbology comparisons and cueing comparisons. Mean deviations and statistical significance for each measure are shown in tables 4 and 5.

Flight performance

In the approach to landing maneuver, statistical significance between symbologies was found for the following measures: position, heading, altitude, and speed (table 4). Cueing effectiveness was determined using pairwise comparisons within a symbology set using the components of the indices. Table 5 shows cueing significance for BOSS for position and for Legacy for heading and speed.

Table 4.
Mean deviations by symbology and significance values between symbologies.

Approach to landing	**Mean**			***p*-value (*p* < .05)**		
Index	Legacy	BOSS	FISH	Legacy/ BOSS	Legacy/ FISH	FISH/ BOSS
Position (feet)	22.683	9.823	15.465	<0.001	0.075	0.151
Heading (deg.)	3.656	2.661	3.900	0.001	0.960	<0.001
Altitude (feet)	9.849	8.816	7.967	0.270	0.007	0.381
Speed (knots)	9.946	6.703	8.184	0.003	0.271	0.225

Table 5.
Cueing mean deviations and significance values for approach to landing.

Approach to landing	**Mean deviation**				***p*-value (*p* < .05)**					
Index	IR	TSAS	Aural	Both*	IR/ TSAS	IR/ Aural	IR/ Both*	TSAS/ Aural	TSAS/ Both*	Aural/ Both*
Position (ft.)										
BOSS	10.27	8.163	6.941	13.92	0.03	0.048	0.347	0.734	0.439	0.443
Heading (deg.)										
Legacy (Level phase)	0.75	0.543	0.888	0.353	0.229	0.672	0.144	0.183	0.949	0.045
Speed (kts)										
Legacy (Level phase)	0.391	0.586	1.361	0.829	0.522	0.017	0.404	0.096	0.607	0.054
Legacy (Landing)	3.234	2.655	3.896	2.551	0.279	0.538	2.15	0.048	0.961	0.237
Legacy (Landing Lateral Drift)	0.322	0.414	0.161	0.127	0.375	0.07	0.046	0.048	0.06	0.305

* "Both" refers to the combined TSAS and Aural display.

Position

The position index indicates pilot deviations from the ideal point in the touchdown zone. The ideal point could be seen visually by aligning the aircraft in the center of a Y-light with the forward light straight ahead of the helicopter and side Y-lights would ideally be centered off the side windows when the dust cleared. BOSS and FISH symbologies provided guidance to the ideal touchdown point, whereas with the Legacy symbology, pilots were forced to determine position using the IR sensor alone. The measurement for analysis was the position where all three wheels of the aircraft first touched down and not the final resting position after the aircraft came to a stop.

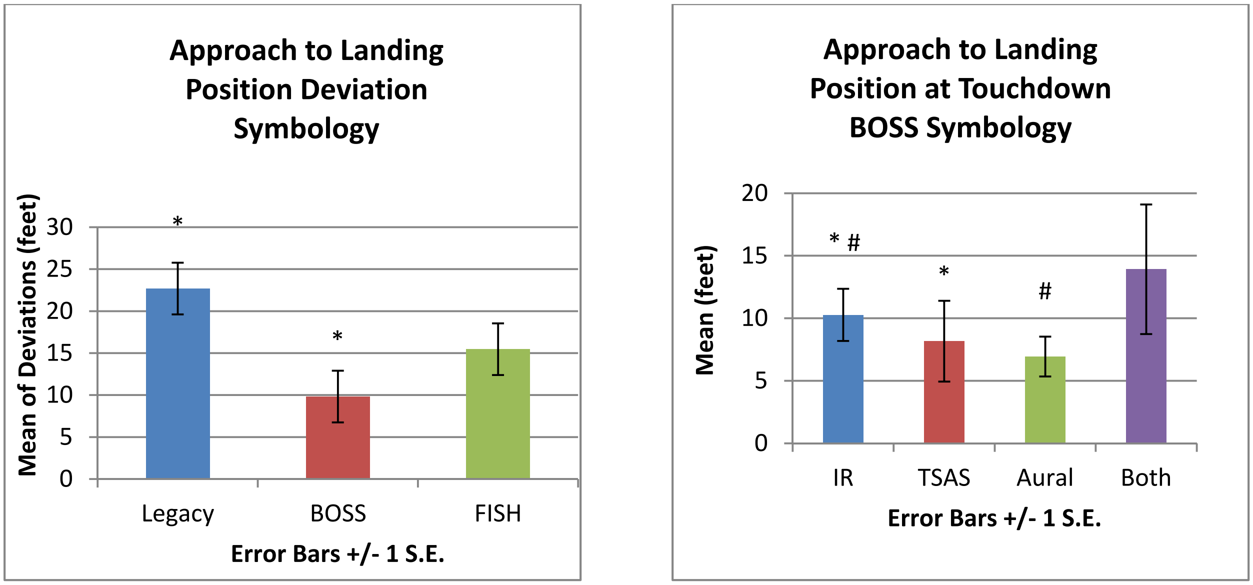


Figure 2. Position index data by symbology (left) and position at touchdown data for BOSS by cueing (right). Matching data labels indicate which symbologies/cueings are statistically significantly different. Note: "Both" refers to the combined TSAS and Aural display.

Symbology. Flight performance for the position index (figure 2 left) showed that BOSS had the lowest mean deviation and pilot performance was significantly better with BOSS than with the Legacy symbology.

Cueing. Figure 2 (right) shows significant differences in touchdown position for cueing within the BOSS symbology. The data indicate that pilot position accuracy improved when BOSS was paired with either the TSAS or Aural cueing displays than when using BOSS paired with only an IR scene.

Heading

During all portions of the approach to landing, pilots were told to maintain a 040 degree heading. The performance measures used to compute the heading deviation index were the standard deviation (SD) of the heading during the level, transition to approach, approach, and transition to landing segments. Heading was not recorded after the landing was completed.

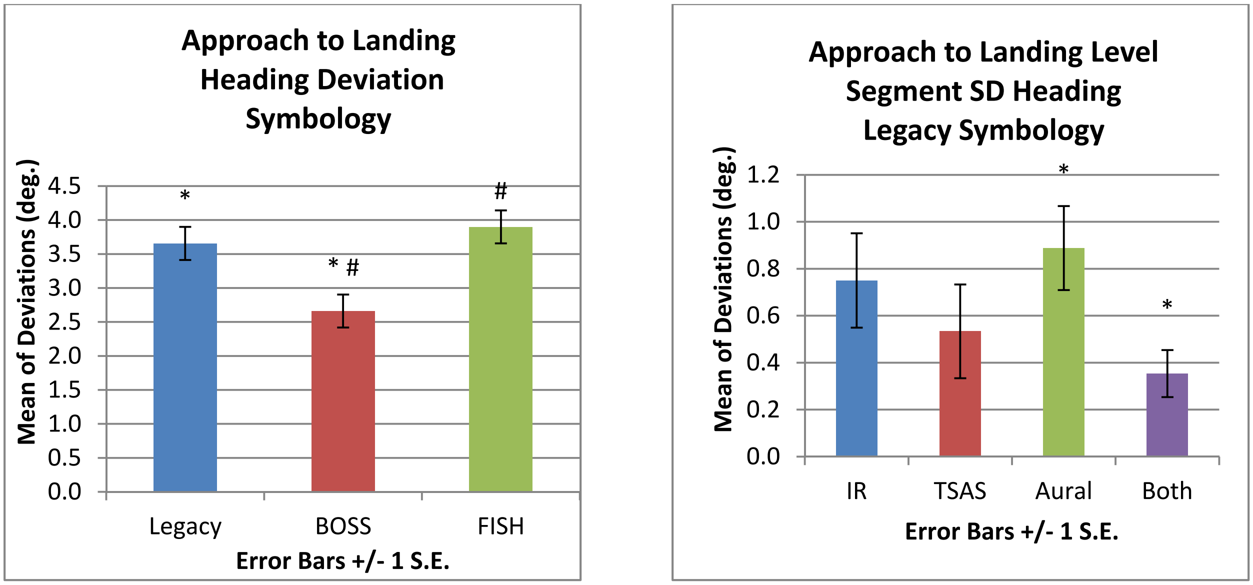


Figure 3. Heading index data by symbology (left) and the SD of heading during the level segment of the maneuver for Legacy by cueing (right). Note: "Both" refers to the combined TSAS and Aural display.

Symbology. Figure 3 (left) shows flight performance for the heading deviation index. The data indicate that pilots performed better while using BOSS symbology for overall heading maintenance. Pilot performance was significantly better with BOSS than with either FISH or Legacy symbologies.

Cueing. Figure 3 (right) shows within symbology, heading performance was affected by cueing in the Legacy symbology set during the level segment of the maneuver. Pilot heading maintenance was significantly better with the TSAS and Aural cueing display than with the Aural cueing display.

Altitude

The only performance measure used for the altitude deviation index was the root mean square deviation (RMSD) of the altitude during the level segment where pilots were required to maintain 250 ft. of altitude. During the rest of the maneuver, the BOSS symbology did not provide data on altitude, but rather a velocity vector, so it was not comparable to the FISH and Legacy symbologies.

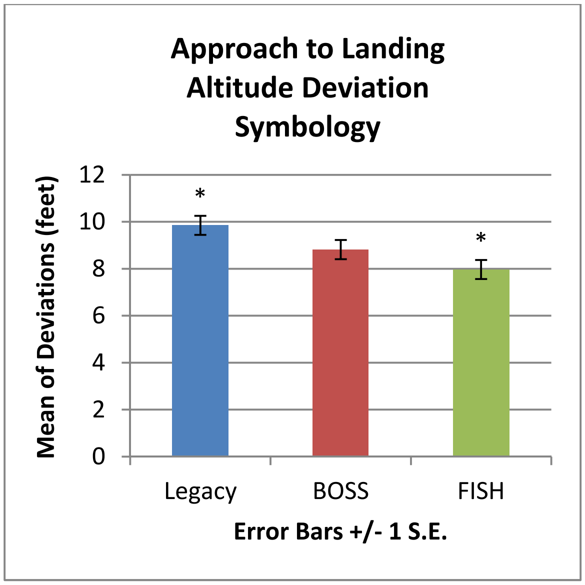


Figure 4. Altitude index data by symbology.

Symbology. Figure 4 shows that flight performance for altitude deviation during the level portion was lowest with FISH symbology. Statistical significance was found between FISH and Legacy symbologies.

Cueing. No significant difference in altitude deviation was found among cueing displays.

Speed

The performance measures used to calculate the speed deviation index were the RMSD of the speeds during the level and approach segments (80 knots), and the difference between the measured speeds and the target speeds in the longitudinal and lateral directions at the moment of touchdown.

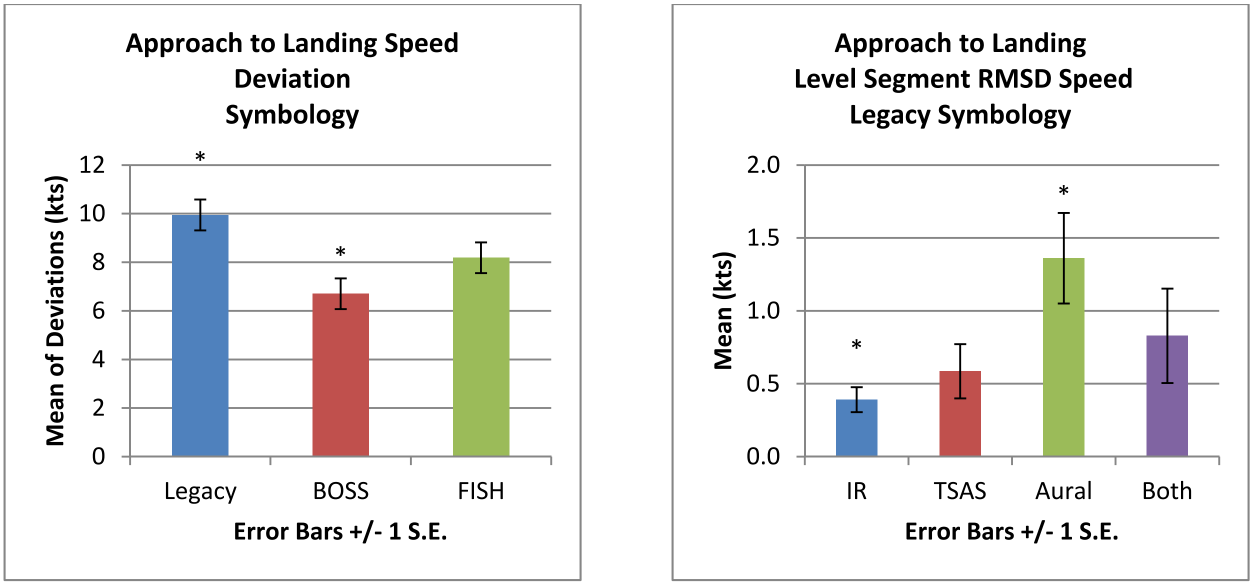


Figure 5. Speed index data by symbology (left) and the RMSD of speed during the level segment for Legacy by cueing (right). Note: "Both" refers to the combined TSAS and Aural display.

Symbology. Figure 5 (left) shows flight performance for the speed index. Overall, speed performance was best when pilots were using advanced symbology. BOSS had the lowest mean deviation for landing speed performance. Statistical analyses indicated that performance was significantly better with BOSS than with Legacy symbology.

Cueing. Figure 5 (right) shows within symbology, cueing effects were seen in both the level and landing phases. In the level phase, pilot deviation from the 80 knot required speed was less with Legacy display (.4 knots) than with the Legacy and Aural cueing display (1.4 knots, p = .017).

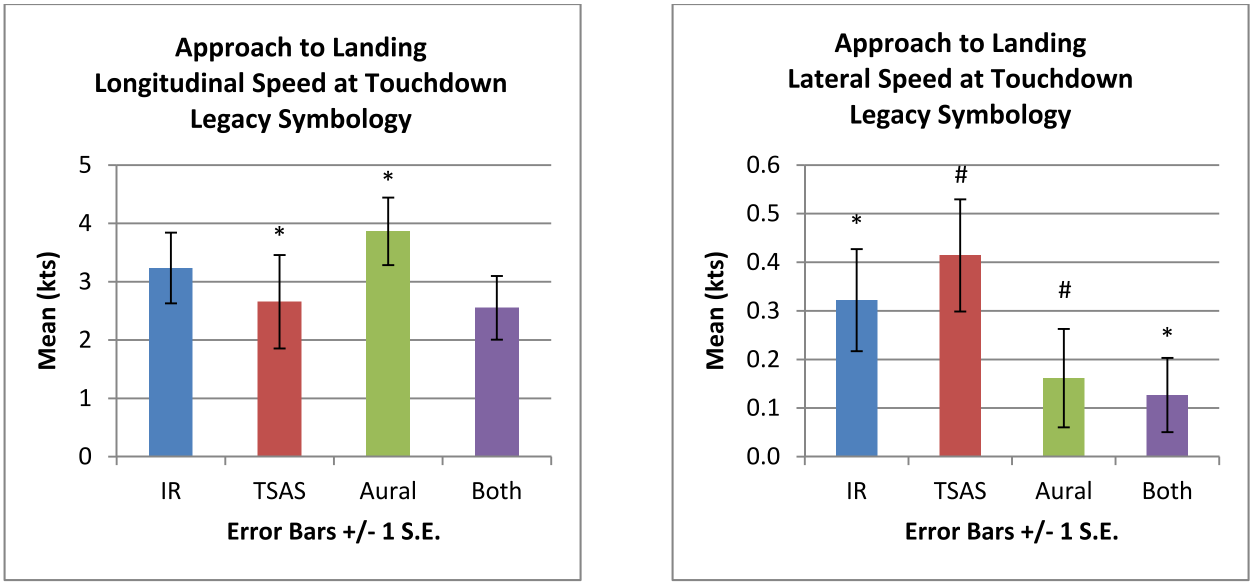


Figure 6. Longitudinal speed at touchdown data (left) and lateral speed at touchdown data (right) for Legacy condition and grouped by cueing. Note: “Both” refers to the combined TSAS and Aural display.

Figure 6 (left) shows cueing significance for the touchdown phase of the approach to land maneuver was found for the Legacy symbology set. Pilots were directed to touch down with 1 to 2 knots of forward (longitudinal) airspeed. The data suggest that forward landing speed was significantly slower with tactile cueing than with the Aural cueing display when flying the Legacy symbology.

Figure 6 (right) shows in the landing phase, pilots were directed to touch down with no lateral drift. Drift performance differences existed for Legacy symbology. Drift performance was best when Legacy symbology was paired with the TSAS and Aural cues display. Drift performance was statistically better when Legacy was paired with the TSAS and Aural cueing display than when paired with only the IR scene. Additionally, performance using the Aural cueing display was significantly better than performance using the TSAS cueing display.

Subjective data

Following the approach to landing maneuver, pilots were asked to rate the effect of cueing displays on handling qualities using the Cooper-Harper Handling Qualities Rating Scale, workload using the Bedford Workload Scale, and usable cue index using the VCI. Table 6 shows that overall ratings indicated pilot preference for BOSS symbology over Legacy symbology. Bedford Workload Scale data indicate that pilots perceived workload to be significantly lower using BOSS than using either Legacy or FISH. Additionally, a cueing effect was found for workload. Pilots reported that workload was significantly lower when symbology was paired with the TSAS and Aural cueing display than when paired with the Aural cueing display (table 7).

Table 6.
Summary of subjective data comparing symbology sets.

Approach to landing	**Mean**			***p*-value (*p* < .05)**		
Measure	Legacy	BOSS	FISH	Legacy/ BOSS	Legacy/ FISH	FISH/ BOSS
Cooper Harper	4.69	3.44	4.25	0.04	0.48	0.08
Bedford	5.25	3.94	4.78	0.04	0.40	0.05
VCI Attitude	3.80	2.53	2.77	0.03	0.12	0.40
VCI Horizontal	3.44	2.00	2.69	0.017	0.12	0.21
VCI Vertical	3.59	1.66	2.50	0.017	0.07	0.06

Table 7.
Summary of subjective test data where significance was found between cueing displays.

Approach to landing	**Mean**				***p*-value (*p* < .05)**					
Index	IR	TSAS	Aural	Both*	IR/ TSAS	IR/ Aural	IR/ Both*	TSAS/ Aural	TSAS/ Both*	Aural/ Both*
Bedford	4.625	4.667	4.833	4.500	0.932	0.445	0.581	0.493	0.216	0.024

* “Both” refers to the combined TSAS and Aural display.

Questionnaire rank data

Table 8 shows pilot rank data sums. The test pilots ranked the order of difficulty for the approach to landing maneuver for all cueing combinations within each visual symbology set from easiest (1) to hardest (4). However, due to a change in the questionnaire format after the second test pilot, only data from test pilots 3 to 8 were used for this analysis. For the Legacy and BOSS symbology sets, pilots ranked the TSAS with Aural combination as the easiest to fly, while for FISH, the TSAS cueing display was ranked the easiest to fly. An overall sum of rankings shows that for the approach to landing maneuver, the TSAS cueing display and the TSAS and Aural cueing display received the same overall score as the easiest to fly. The IR condition (no supplemental cues) was the most difficult to fly overall.

Table 8.
Cumulative summation of ranking from questionnaires.

Pilot ranking	IR	TSAS	Aural	TSAS and Aural
Legacy	21	13	14	12
BOSS	19	12	18	11
FISH	17	11	19	13
Total	57	36	51	36

Approach to landing results summary

Table 9 shows summary results for the approach to landing maneuver. Overall, BOSS symbology paired with Tactile and Aural produced the best performance and were preferred over other conditions. Subjective data and rank data findings agreed that the test pilots most preferred the TSAS and Aural cueing display, and that the Aural cueing display alone was the least preferred.

Table 9.
Approach to landing summary.

Measure	**Symbology**	**Cueing Display**
Flight	BOSS	TSAS and Aural
Rank	N/A	TSAS and Aural
Subjective	BOSS	TSAS and Aural
Overall	BOSS	TSAS and Aural

Approach to hover

Flight performance

In the approach to hover maneuver, statistical significance between the visual symbologies was found for the following measures: position, heading, altitude, and speed (table 10). Cueing effectiveness was determined using pairwise comparisons for a symbology set using the components of the indices. Table 11 shows cueing significance for BOSS for position, heading, and altitude. Significance was found for FISH symbology for heading and speed, and for Legacy symbology for speed.

Table 10.
Mean deviations by symbology and significance values between symbologies.

Approach to hover	**Mean**			***p*-value (*p* < .05)**		
Index	Legacy	BOSS	FISH	Legacy/ BOSS	Legacy/ FISH	FISH/ BOSS
Position(ft.)	50.904	9.681	33.963	<0.001	0.006	<0.001
Heading (deg.)	6.914	5.282	6.626	0.080	1.000	0.066
Altitude (ft.)	19.965	9.525	10.698	<0.001	<0.001	0.200
Speed (kts)	7.836	6.132	5.364	0.150	0.003	0.408

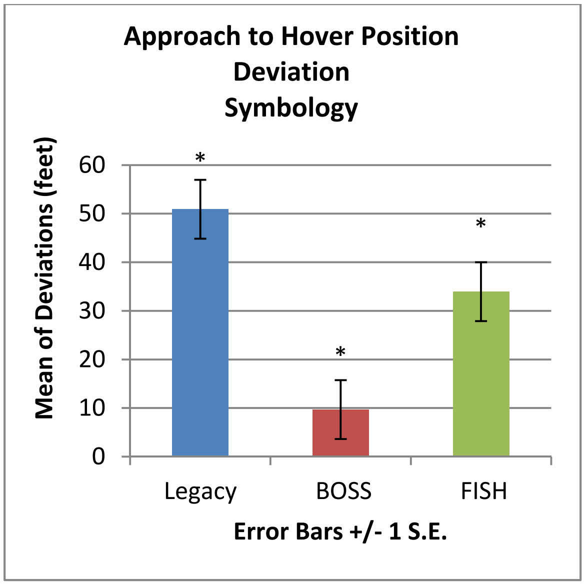
Table 11.
Cueing mean deviations and significance values for approach to hover.

Approach to hover	**Mean deviation**				***p*-value (*p* < .05)**					
Measure	IR	TSAS	Aural	Both*	IR/ TSAS	IR/ Aural	IR/ Both*	TSAS/ Aural	TSAS/ Both*	Aural/ Both*
Position (ft.)										
BOSS (Hover)	3.98	11.796†	6.526	4.697	0.012	0.105	0.562	0.426	0.137	0.669
Heading (deg.)										
BOSS	1.13	1.42	0.963	0.946	0.224	0.429	0.291	0.137	0.031	0.889
FISH	1.448	1.329	1.072	0.851	0.819	0.141	0.012	0.271	0.028	0.289
Altitude (ft.)										
BOSS (RMSD Level)	7.363	7.441	8.291	9.195	0.921	0.41	0.033	0.481	0.128	0.413
BOSS (RMSD Hover)	1.79	1.216	1.554	1.249	0.012	0.392	0.143	0.63	0.703	0.821
Speed (kts)										
FISH (Level)	0.744	1.664†	0.756	0.879	0.100	0.825	0.337	0.036	0.313	0.459
Legacy (Approach)	5.401	6.472	8.656	6.971	0.269	0.035	0.543	0.303	0.982	0.423

*"Both" refers to the combined TSAS and Aural display.
† Outlier included in the mean.

Position

The index for approach to hover position deviation was derived from the RMSD of the lateral and longitudinal positions during the hover segment only, therefore no longitudinal data were included in the analysis for the level flight, transition to approach, approach, and transition to hover segments. The lateral position data during those same segments could not be used due to the differences in how BOSS and FISH symbologies plot the course to the target hover zone.



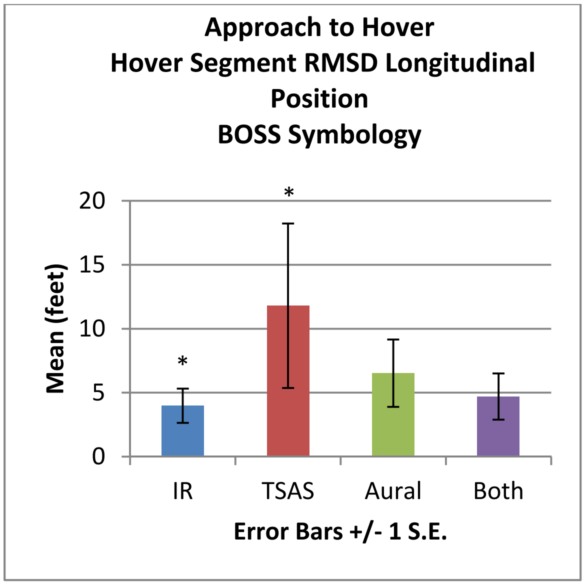


Figure 7. Position index data by symbology (left) and the RMSD of the longitudinal position deviation data during the hover segment, for BOSS by cueing (right).
Note: "Both" refers to the combined TSAS and Aural display.

Symbology. Figure 7 (left) shows that pilot overall position maintenance for the approach to hover maneuver was better when using BOSS symbology. Statistically significant differences in position performance were found among all symbology sets. Pilot position performance was significantly worse with Legacy symbology than with either BOSS or FISH symbologies.

Cueing. Figure 7 (right) shows a significant difference between BOSS and BOSS paired with TSAS. The results are inconclusive due to an outlier existing in the data.

Heading

The heading deviation index was computed from the SD of the heading during the level, transition to approach, approach, and transition to hover segments, and the RMSD of the hover segment.

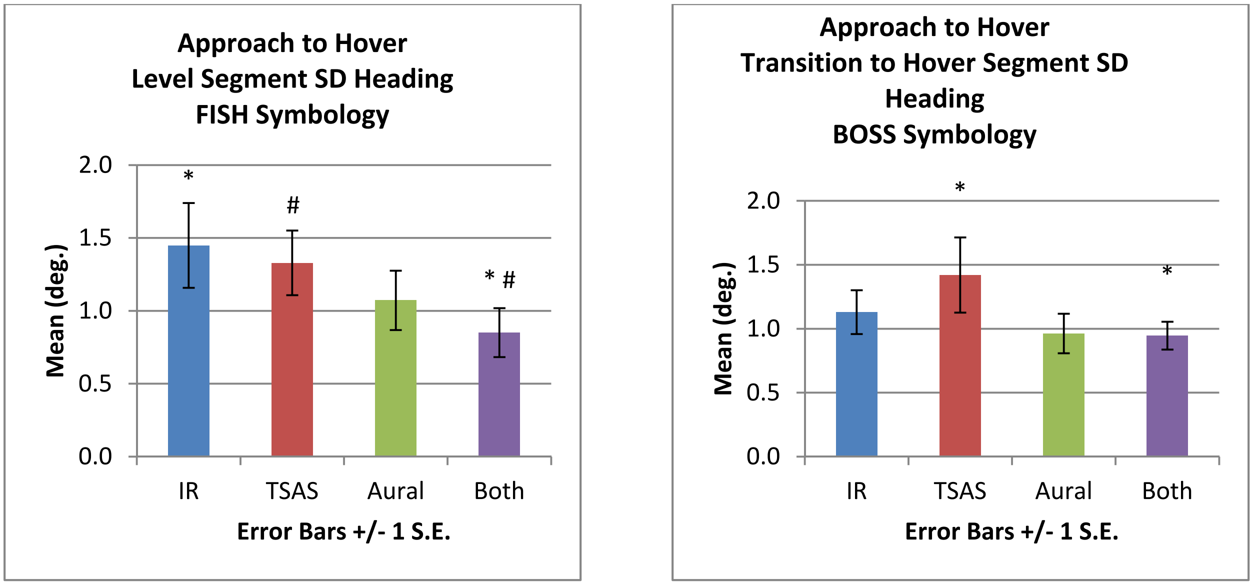


Figure 8. The SD of heading data during the level segment for FISH (left) and during the transition to hover segment for BOSS (right). Note: "Both" refers to the combined TSAS and Aural display.

Symbology. No significant differences in heading deviation were found among symbology sets.

Cueing. Figure 8 shows cueing significance for heading. In the level phase, significance was found for the FISH symbology and for the transition to hover phase for the BOSS symbology. During the level flight portion of the maneuver, FISH with the TSAS and Aural cueing display was better than FISH and FISH paired with TSAS cueing displays.

In the transition to hover portion of the maneuver, performance was better with BOSS symbology when paired with the TSAS and Aural cueing display than the TSAS cueing display.

Altitude

The altitude deviation index was computed from the RMSD of the altitude during the level and hover segments of the maneuver. Note that BOSS does not provide altitude command guidance in the level segment.

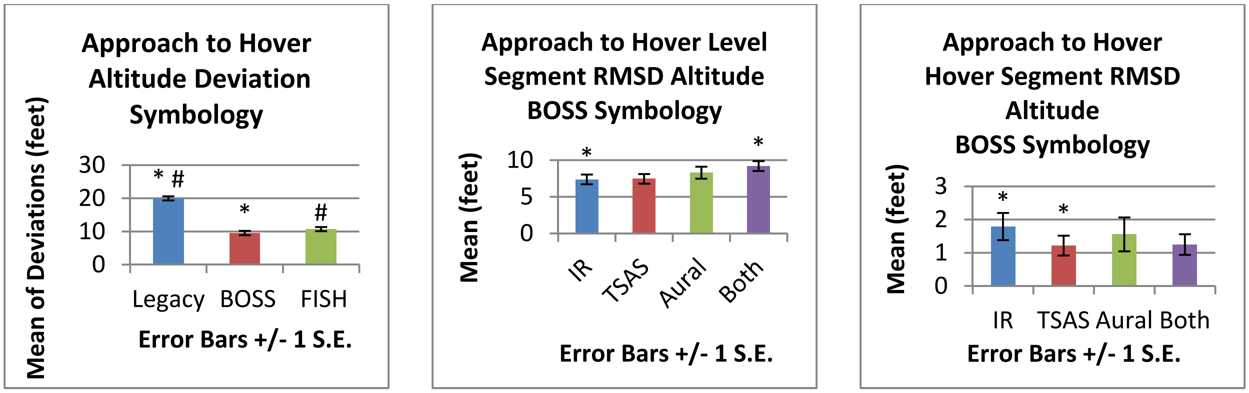


Figure 9. Altitude index data by symbology (left), and altitude RMSD for level and hover segments (middle and right). Note: "Both" refers to the combined TSAS and Aural display.

Symbology. Figure 9 (left) indicates altitude maintenance was better for BOSS and FISH symbologies than for Legacy symbology.

Cueing. Figure 9 (middle and right) shows cueing significance for altitude. Significant differences were found in both the level and hover segments. In the level segment, the test pilots were better able to maintain desired altitude with BOSS than with BOSS paired with the TSAS and Aural cueing display.

Speed

The speed deviation index was computed using the RMSD of the speed during the level and approach segments. Speed data for the transition and hover segments were not analyzed.

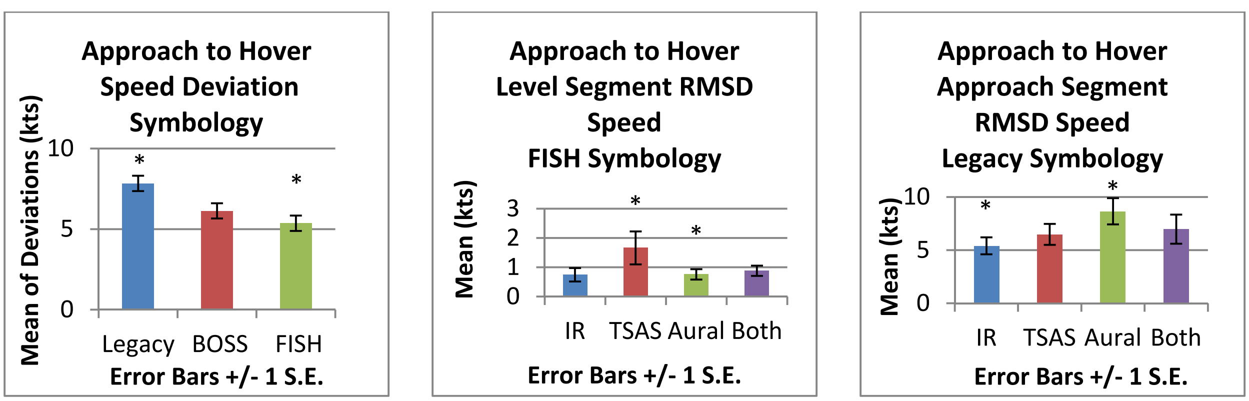


Figure 10. Speed index data by symbology (left), and speed RMSD for level and approach segments (middle and right). Note: "Both" refers to the combined TSAS and Aural display.

Symbology. Figure 10 (left) shows approach to hover speed deviation data which indicate that performance using FISH symbology was significantly better than using Legacy symbology.

Cueing. Figure 10 (middle and right) shows speed performance was significantly different for both Legacy and FISH symbologies. The significance between FISH paired with Aural and FISH paired with TSAS occurred in the level phase of the maneuver and might be attributed to an outlier in the data. The significance in the legacy symbology occurred in the approach segment of the maneuver. The data indicate pilots flew the approach faster when provided Aural cueing over Legacy symbology.

Subjective data

Ratings show pilots preferred BOSS symbology over Legacy symbology for all indices. Pilots rated BOSS and FISH symbologies over Legacy symbology on the vertical VCI (table 12).

Table 12.
Summary of subjective data.

Approach to hover	**Mean**			***p*-value (*p* < .05)**		
Index	Legacy	BOSS	FISH	Legacy/ BOSS	Legacy/ FISH	FISH/ BOSS
Cooper Harper	5.5313	3.9063	4.6250	0.017	0.324	0.233
Bedford	5.5938	4.2188	5.1563	0.020	0.445	0.128
VCI Attitude	3.9478	2.4991	2.7706	0.012	0.068	0.208
VCI Horizontal	3.5625	2.0313	2.5938	0.018	0.079	0.293
VCI Vertical	3.7188	1.7813	2.5313	0.018	0.021	0.108

Approach to hover summary

Table 13 indicates that for the approach to hover maneuver, pilots preferred and performed better with the BOSS symbology set over Legacy and Fish. Pilots performed better with the TSAS and Aural cueing display over other cueing displays, independent of symbology set.

Table 13.
Summary of symbology sets and cueing displays for Approach to Hover.

Measure	**Symbology**	**Cueing Display**
Flight	BOSS	TSAS and Aural
Rank	N/A	N/A
Subjective	BOSS	N/A
Overall	BOSS	TSAS and Aural

Hover

Flight performance

In the hover maneuver, significant differences were found between symbology sets for the following measures: position, heading, and altitude (table 14). Table 15 shows that, when using the FISH symbology, the Aural cueing display was significantly better for heading control than the Aural cueing display combined with TSAS.

Table 14.
Mean deviations by symbology and significance values between symbologies.

Hover	**Mean**			***p*-value (*p* < .05)**		
Index	Legacy	BOSS	FISH	Legacy/ BOSS	Legacy/ FISH	FISH/ BOSS
Position(ft.)	28.447	4.896	14.357	<0.001	<0.001	<0.001
Heading (deg.)	2.028	1.891	1.017	0.595	0.024	0.312
Altitude (ft.)	3.576	1.062	3.019	<0.001	0.231	<0.001

Table 15.
Cueing mean deviations and significance values for Hover.

Hover	**Mean deviation**				***p*-value (*p* < .05)**					
Heading (deg.)	IR	TSAS	Aural	Both*	IR/ TSAS	IR/ Aural	IR/ Both*	TSAS/ Aural	TSAS/ Both*	Aural/ Both*
FISH*	0.944	0.834	0.753	1.535	0.095	0.251	0.661	0.251	0.385	0.026*

* "Both" refers to the combined TSAS and Aural display.

Position

For the hover maneuver, the position deviation index was calculated from the RMSD of the lateral and longitudinal positions during the hover.

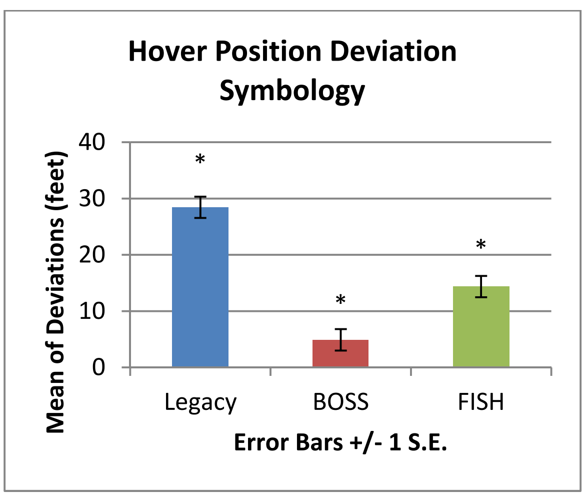
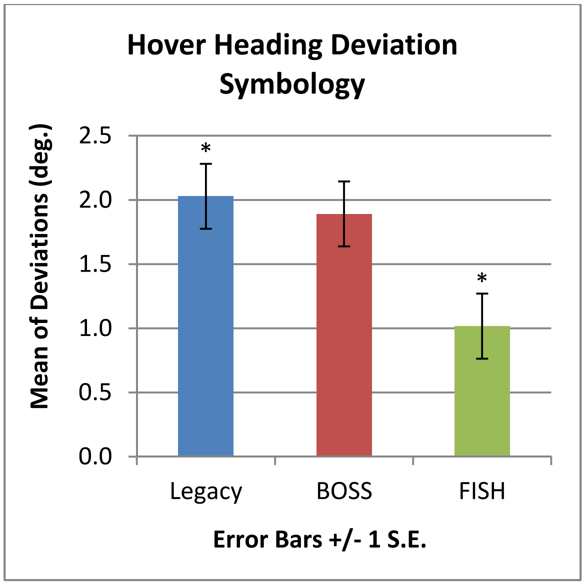


Figure 11. Position index data grouped by symbology.

Symbology. Figure 11 shows significance in hover position deviation. All symbology sets were significantly different from each other. BOSS symbology produced the best performance of the three.

Cueing. No significant difference in altitude deviation was found among cueing displays.

Heading



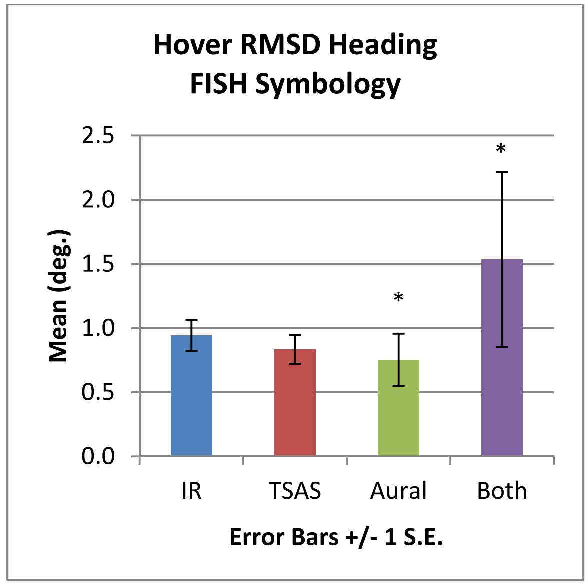


Figure 12. Heading index data grouped by symbology (left) and the RMSD of heading (right). Note: "Both" refers to the combined TSAS and Aural display.

Symbology. Figure 12 (left) shows significance in hover heading deviation. Pilot heading maintenance was statistically better for the FISH than the Legacy symbology.

Cueing. Figure 12 (right) shows cueing significance for heading during the hover maneuver. Significance was found between FISH paired with the Aural cueing display and FISH paired with the TSAS and Aural cueing display. Note that this outcome is the result of an outlier in the data (Outlier chart, appendix c).

Altitude

The altitude deviation index was computed from the RMSD of the altitude during the hover maneuver.

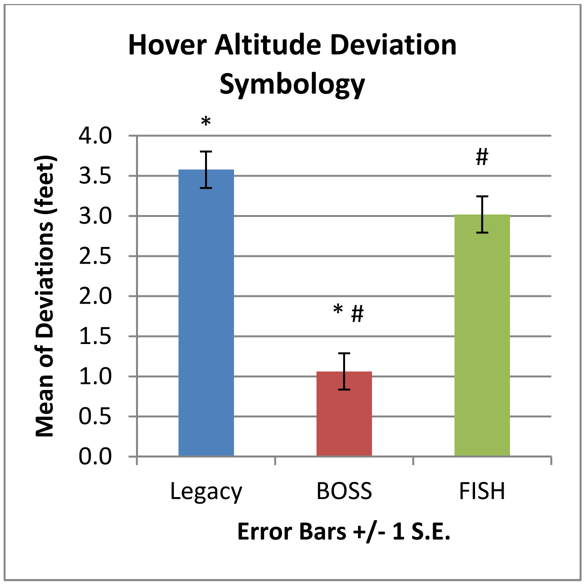


Figure 13. Altitude index data by symbology.

Symbology. Figure 13 shows altitude maintenance performance was statistically better with BOSS symbology than with either FISH or Legacy symbologies.

Cueing. No significant difference in altitude deviation was found among cueing displays.

Questionnaire rank data

Pilots ranked the order of difficulty for the hover maneuver for all cueing combinations within each visual symbology set from easiest (1) to hardest (4). Table 16 shows the TSAS cueing display was ranked to be the easiest to fly, followed by the TSAS and Aural cueing display. The Aural cueing display was ranked the most difficult to fly.

Table 16.
Summations of rankings from questionnaires.

Pilot Ranking	IR	TSAS	Aural	TSAS and Aural
Legacy	20	8	19	13
BOSS	20	9	19	12
FISH	15	7	21	17
Total	55	24	59	32

Subjective data

Pilots preferred the BOSS over Legacy symbology for all indices. Additionally, the BOSS symbology was rated better than the FISH symbology on Cooper Harper, Bedford Workload Scale, and the Vertical VCI.

Table 17.
Summary of subjective data for hover.

Hover	Mean			*p*-value ($p < .05$)		
Index	Legacy	BOSS	FISH	Legacy/ BOSS	Legacy/ FISH	FISH/ BOSS
Cooper Harper	5.1875	3.5313	4.562	0.018	0.398	0.042
Bedford	5.3125	3.7188	5.0313	0.020	0.779	0.027
VCI Attitude	3.6878	2.2497	2.7288	0.012	0.161	0.205
VCI Horizontal	3.1875	1.9375	2.5938	0.012	0.293	0.125
VCI Vertical	3.500	1.5938	2.5625	0.012	0.074	0.017

Hover summary

Table 18 indicates that for the hover maneuver, the BOSS symbology and the Aural cueing display and the TSAS cueing display produced the best performance and were preferred over other conditions.

Table 18.
Summary of symbology sets and cueing displays for the hover maneuver.

Measure	Symbology	Cueing Display
Flight	BOSS	Aural
Rank	N/A	TSAS
Subjective	BOSS	N/A
Overall	BOSS	Aural or TSAS

Sidestep

Flight performance

Although the sidestep maneuver began and ended with 20 s hovers, only the sidestep segment data were analyzed.

Table 19.
Mean deviations by symbology and significance values between symbology sets.

Sidestep	Mean			*p*-value ($p < .05$)		
Index	Legacy	BOSS	FISH	Legacy/ BOSS	Legacy/ FISH	FISH/ BOSS
Position (ft.)	80.340	12.160	13.015	<0.001	<0.001	0.763

Table 20.
Cueing mean deviations and significance values for sidestep.

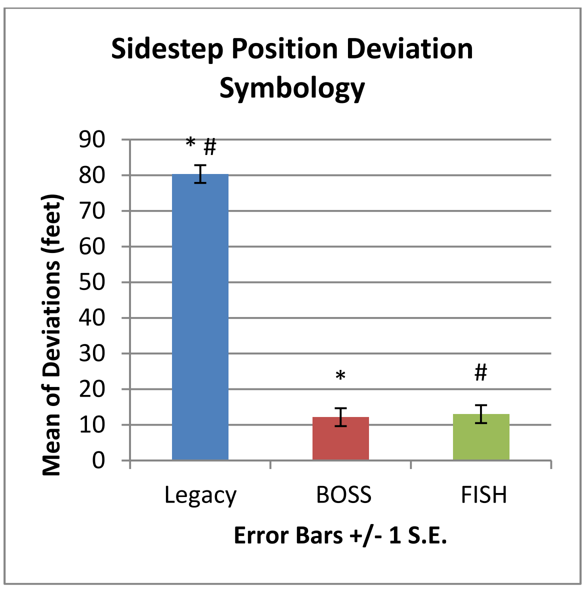
Sidestep	Mean deviation				*p*-value (*p* < .05)					
Measure	IR	TSAS	Aural	Both*	IR/ TSAS	IR/ Aural	IR/ Both*	TSAS/ Aural	TSAS/ Both*	Aural/ Both*
Position (ft.)										
FISH	10.064	6.695	13.122	22.18	0.134	0.225	0.019	0.017	0.011	0.305
Heading (deg.)										
FISH	0.838	1.157	0.806	1.154	0.258	0.131	0.488	0.017	0.635	0.074
Speed (kts)										
Legacy	5.04	5.352	4.988	4.885	0.133	0.832	0.15	0.01	0.013	0.506

* "Both" refers to the combined TSAS and Aural display.

In the sidestep maneuver, statistical significance between symbologies was found for the position index (table 19). Table 20 shows cueing significance for the FISH symbology for position and heading, and for Legacy symbology for speed.

Position

For the sidestep maneuver, the position deviation index was computed from the RMSD of the lateral position during the sidestep segment.



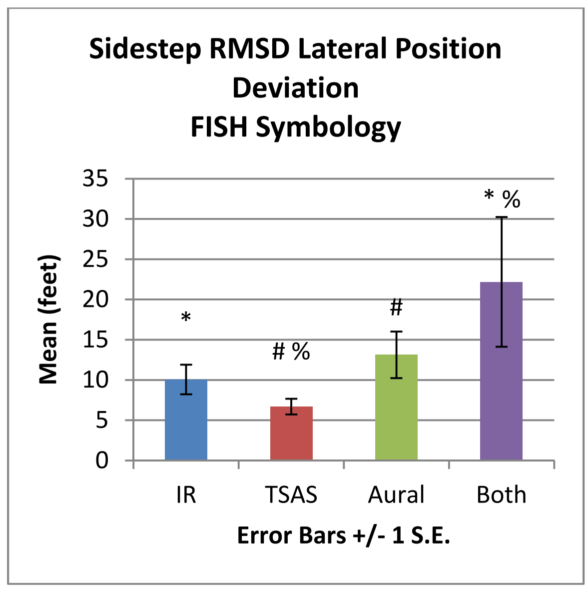


Figure 14. Position index data grouped by symbology (left) and the RMSD of lateral position deviation data for FISH grouped by cueing (right). Note: "Both" refers to the combined TSAS and Aural display.

Symbology. Figure 14 (left) shows pilots performed significantly better when using the BOSS and FISH symbologies than when using the Legacy symbology.

Cueing. Figure 14 (right) shows for the FISH symbology set, multiple cueing differences were found. Performance using the TSAS cueing display was significantly better than the Aural cueing display and the TSAS and Aural cueing display. Additionally, the FISH symbology was significantly better than the TSAS and Aural cueing display.

Heading

The heading deviation index was computed from the heading RMSD during the sidestep segment of the maneuver.

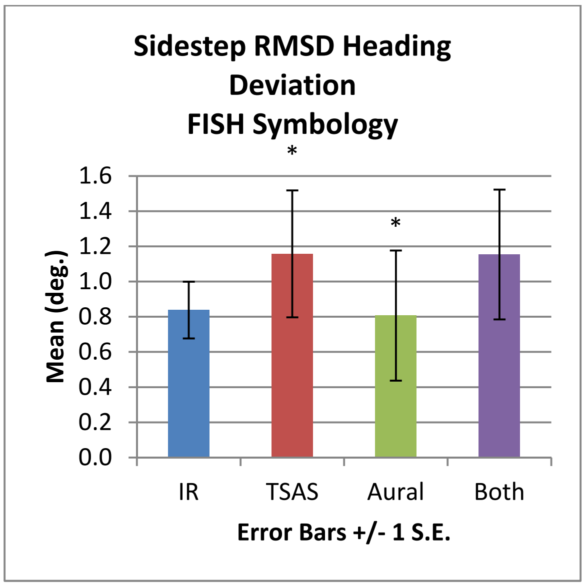


Figure 15. The RMSD of heading for FISH and grouped by cueing. Note: "Both" refers to the combined TSAS and Aural display.

Symbology. No significance was found in the visual symbology data.

Cueing. Figure 15 shows heading maintenance performance with the FISH symbology for sidestep was better when paired with the Aural cueing display than when paired with the TSAS cueing display.

Speed

The speed index was computed from the maximum velocity measured during the sidestep maneuver.

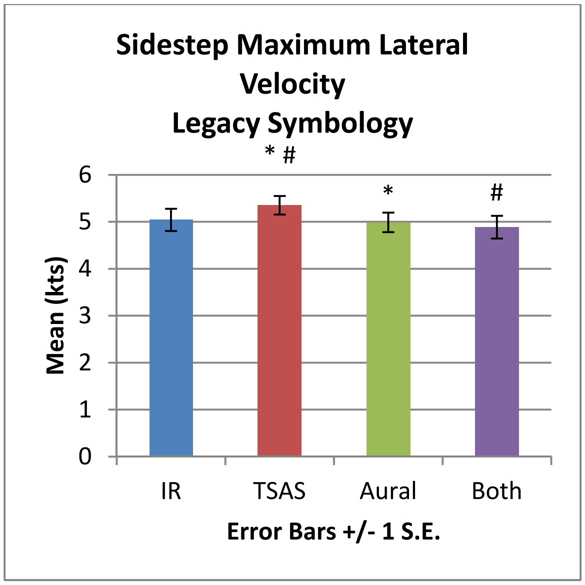


Figure 16. The maximum lateral velocity data for the Legacy symbology grouped by cueing. Note: "Both" refers to the combined TSAS and Aural display.

Symbology. No significance was found in the symbology data.

Cueing. The data indicated in Figure 16 shows with Legacy symbology the sidestep velocity was faster when paired with the TSAS cueing display than with Aural or TSAS and Aural cueing displays.

Questionnaire rank data

The test pilots ranked the order of difficulty for the sidestep maneuver for all cueing combinations within each visual symbology set from easiest (1) to hardest (4). Table 21 shows the TSAS cueing display was ranked as the easiest to fly, followed by the TSAS and Aural cueing display. The Aural cueing display was ranked the most difficult to fly.

Table 21.
Summations of rankings from questionnaires.

Pilot ranking	IR	TSAS	Aural	TSAS and Aural
Legacy	18	9	19	14
BOSS	18	8	19	15
FISH	13	7	22	18
Total	49	24	60	47

Subjective ratings

Table 22 data indicate pilots rated the BOSS symbology over the Legacy symbology for all VCIs.

Table 22.
Summary of subjective data comparing symbology sets.

Sidestep	**Mean**			***p*-value (*p* < .05)**		
Index	Legacy	BOSS	FISH	Legacy/ BOSS	Legacy/ FISH	FISH/ BOSS
Cooper Harper	4.9688	4.1563	4.3125	0.079	0.395	0.799
Bedford	5.3750	4.5000	4.9688	0.079	0.528	0.181
VCI Attitude	3.7397	2.6138	2.6459	0.012	0.123	0.499
VCI Horizontal	3.0625	2.0625	2.3438	0.011	0.233	0.671
VCI Vertical	3.4688	2.0313	2.5313	0.017	0.150	0.105

Table 23.
Summary of subjective test data where significance was found between cueing displays.

Sidestep	**Mean**				***p*-value (*p* < .05)**					
Index	IR	TSAS	Aural	Both*	IR/ TSAS	IR/ Aural	IR/ Both*	TSAS/ Aural	TSAS/ Both*	Aural/ Both*
VCI Horizontal	2.6667	2.5000	2.3333	2.4583	0.244	0.027	0.064	0.180	0.496	0.461

* “Both” refers to the combined TSAS and Aural display.

Symbology. Table 22 shows that in the sidestep maneuver, pilots rated the BOSS symbology over the Legacy symbology for all VCIs.

Cueing. Table 23 shows cueing significance was found for the Horizontal VCI rating which suggests that pilots preferred the Aural cueing display over the IR condition.

Sidestep summary

Table 24 indicates that for the sidestep maneuver the BOSS symbology paired with the TSAS cueing display produced the best performance and was preferred over other displays.

Table 24.
Summary of symbology sets and cueing displays.

Measure	**Symbology**	**Cueing Display**
Flight	BOSS	TSAS
Rank	N/A	TSAS
Subjective	BOSS	Aural
Overall	BOSS	TSAS

Biometric data

The physiological measures of psychological stress resulting from the pilot's cognitive workload were measured through HRV, GSR, and RR. These measurements were chosen because of "minimal invasiveness" and potential for future use in aircraft. The biometric data were analyzed with BIOPAC's® AcqKnowledge® and MathWorks'® MATLAB® software. Full biometric results are located in appendix d.

Table 25.
Summary of conditions with the lowest biometric stress responses by maneuver and measure based on mean findings.

Maneuver	Mean Heart Rate	Mean Respiratory Interval	Mean Galvanic Skin Response	Heart Rate Variability Ratio
Approach to Landing	BOSS IR	Legacy TSAS	FISH IR	BOSS TSAS and Aural
Approach to Hover	FISH IR	BOSS IR	FISH TSAS	FISH TSAS and Aural
Hover	FISH IR	Legacy TSAS	BOSS Aural	FISH TSAS and Aural
Sidestep	FISH IR	Legacy TSAS	BOSS TSAS	Legacy TSAS

Condition-specific effects for each significant biometric outcome variable

Mean respiration rate interval

Pairwise post-hoc tests of the main effect for condition on mean respiration interval (controlling for the non-significant effect of maneuver), demonstrated the following significant pairwise differences:

- Legacy TSAS > Legacy IR (Diff = 0.11, $p = 0.018$)

Legacy IR demonstrated a significantly lower mean inter-peak-interval for respiration than Legacy TSAS, which suggests that pilots' stress levels were significantly lower in Legacy TSAS than in Legacy IR condition.

Mean GSR

Pairwise post-hoc tests of the main effect for condition on mean tonic GSR (controlling for the non-significant effect of maneuver) demonstrated the following significant pairwise differences:

- Legacy Aural > BOSS TSAS (Diff = 4.966, $p = 0.002$)
- Legacy Aural > BOSS Aural (Diff = 4.251, $p = 0.028$)
- Legacy Aural > FISH IR (Diff = 5.156, $p < .001$)
- Legacy Aural > FISH TSAS (Diff = 4.454, $p = 0.008$)

- Legacy Aural > FISH Aural (Diff = 4.675, $p = 0.004$)
- Legacy Aural > FISH TSAS and Aural (Diff = 4.262, $p = 0.021$)

Legacy Aural demonstrated a Tonic GSR level that was consistently and significantly higher than several other conditions, indicating that pilots' stress levels were significantly higher in this condition than BOSS TSAS, BOSS Aural, and all FISH cueing conditions. The differences between Legacy Aural and Legacy TSAS (3.718), Legacy TSAS and Aural, and BOSS TSAS and Aural (3.460) were approaching significance ($p < 0.1$).

Heart rate variability

HRV Sympathetic: Vagal Proportion Ratio. While not sensitive to condition effects in the present test, HRV appeared to be quite sensitive to changes between maneuvers. Like HR, HRV data are extracted from the ECG signal, which was consistently the strongest and most accurate data collected (it was very resistant to movement artifact). HRV is divided into two proportion categories based on a spectral density analysis of frequencies; these categories are Sympathetic Activity (correlates with higher stress levels) and Vagal Activity (correlates with lower stress levels). A ratio of the proportion of variance attributed to Sympathetic Activity to the variance attributed to Vagal Activity provides a single measure of HRV; higher levels of this ratio indicate higher levels of stress.

A post-hoc analysis of the significant effect for Maneuver on HRV Ratio indicated the following significant differences:

- Sidestep < Hover (Diff = 2.889, $p < .001$)
- Sidestep < Approach to Hover (Diff = 2.346, $p = 0.004$)
- Sidestep < Approach to Landing (Diff = 3.908, $p = 0.016$)

The sidestep maneuver demonstrated a significantly lower HRV ratio than all other maneuvers, which would suggest that pilots' stress levels were lowest while completing this maneuver.

Discussion

It is important to note that these limited results were attained from eight highly experienced test pilots performing flight maneuvers of short duration during relatively comfortable and stress-free simulated flight. As such, the results cannot be generalized and interpreted as applicable to all Army aviator experience levels or to performance during actual flight conditions. Further assessment of a broader array of aviator experience under operational conditions (e.g., fatigue, workload) is recommended to fully understand how these displays and cueing combinations might perform under real-world conditions. Final determinations of the operational significance of these findings (i.e., vs. statistical significance) are deferred to the test sponsor.

Approach to landing

The results for the approach to landing maneuver indicate that for position maintenance, BOSS symbology performed significantly better than Legacy symbology by an average of approximately 12 ft. In other words, pilots flying with Legacy symbology landed an average of 12 ft. further from the intended touchdown point than pilots flying the BOSS symbology—an operationally significant difference. In addition, greater performance was observed when pilots utilized BOSS symbology when paired with either the TSAS or Aural cueing displays.

Heading maintenance performance was significantly better with BOSS symbology when compared with Legacy and FISH, although less than 1° of difference. It is suspected that this is due to the presence of a color heading tape within the BOSS symbology which is easily referenced by the pilot. In the Legacy condition, heading maintenance was better with the TSAS and Aural cueing display than with the Aural cueing display, indicating a beneficial synergy between tactile and aural cueing.

Altitude and speed maintenance was better with FISH (approximately 2 ft.) and BOSS (approximately 3 knots) symbologies, respectively, than with Legacy symbology. These results likely highlight the benefits of command guidance in advanced flight symbologies.

Level segment speed when using Legacy symbology was better alone than with the Aural cueing display. This reflects test pilot comments that the aural cues were distracting and annoying.

When using the Legacy symbology, pilots had a slower (i.e., better) touchdown speed with TSAS cueing than when the Legacy symbology was paired with the Aural cueing display. This is likely attributed to the cueing synergy of tactile and visual cues which provided a multisensory awareness (a feeling) of rate of closure when using the Legacy symbology, which lacked the speed guidance provided by BOSS and FISH.

The test pilots ranked the order of difficulty for approach to landing for each cueing display within each symbology set. Overall, the TSAS and the TSAS and Aural cueing displays were ranked to be the easiest to fly the approach to landing (Figure 17). These results support the impression that supplemental cueing enhances pilot confidence and situational awareness.

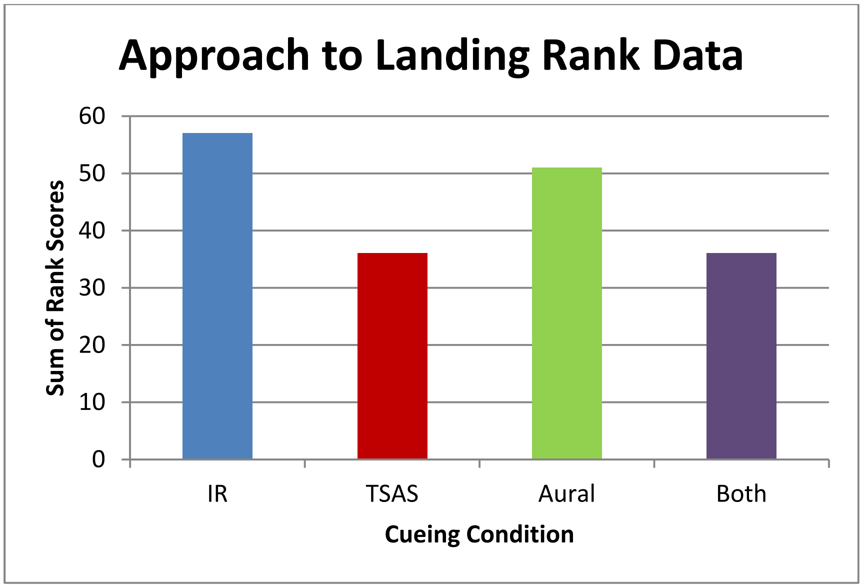


Figure 17. Sum of pilots' rank scores for approach to landing. Note: "Both" refers to the combined TSAS and Aural display.

Biometric data showed no consistent relationship to the approach to landing measures. While mean HR reflected the favorable performance of BOSS, HRV data supported test pilot comments favoring BOSS with TSAS and Aural cueing.

For all approach to landing subjective measures, pilots rated BOSS better than Legacy. The Bedford Workload Scale showed that pilots' perceived workload was less when using BOSS than Legacy or FISH symbologies. The data indicated overall BOSS symbology and the TSAS and Aural cueing display produced the best performance and were preferred. The test pilots reported that performance using BOSS was enhanced by supplemental cues and reported having sufficient spare capacity to perform other tasks.

Approach to hover

The results for the approach to hover maneuver indicate that for position maintenance, BOSS performed, on average, significantly better (9.7 ft. from the desired hover position) than both the Legacy and FISH symbologies (50.9 ft. and 33.9 ft., respectively). This substantial difference is likely due to the intuitive transition design features (Approach to Hover) of the BOSS symbology.

Lateral position with BOSS symbology appeared better when paired only with the IR sensor alone. However, the results are inconclusive due to an outlier that existed in the data. Because of the small number of participants (*n* = 8), the decision was made to not remove outliers from the data when they were analyzed. To interpret the findings, it was necessary to explore individual pilot performance. In this exploration, it was found that one pilot's RMSD data for longitudinal position was more than three standard deviations from the mean, and the pilot performed the approach out of standards and did not correct hover position. All other pilots' position performances in the TSAS condition were comparable to the IR condition. The outlier chart is in appendix A. Additional research is needed with a larger number of participants to determine if significance actually exists between the cueing conditions.

Heading data for BOSS and FISH during the transition to hover and level flight segment indicate that heading maintenance was better for the TSAS and Aural cueing display (although within just 1°) over the TSAS cueing display. It is suspected that TSAS and Aural cues enhanced awareness of heading maintenance contributing to better performance.

Results for altitude maintenance during the approach to hover maneuver indicate altitude performance was better using either BOSS or FISH than it was with Legacy. Hover segment altitude maintenance with BOSS symbology was better when paired with the TSAS cueing display, over BOSS paired with only an IR sensor. Notably, for the level segment, BOSS altitude maintenance was better when paired with only an IR sensor compared with the TSAS and Aural cueing display. The results may suggest that the parameters for altitude maintenance cueing were set too close causing pilot distraction from excessive aural cueing.

Results for speed performance for the approach to hover maneuver indicate that performance with FISH was significantly better than Legacy by approximately 2.5 knots. Speed data during the level segment when using FISH indicate that speed maintenance was better with the aural cueing display than with the TSAS cueing display due to “check speed” aural cueing. TSAS does not provide speed cueing during the level segment.

The test pilots ranked BOSS over Legacy for all indices. Additionally, the test pilots ranked FISH over Legacy for the Vertical VCI. As with the Approach to Landing, these results likely highlight the benefits of command guidance provided in advanced flight symbologies.

Biometric data failed to consistently predict flight performance or test pilot ratings. Mean respiratory interval indicated lower stress during the BOSS IR condition, but various combinations involving FISH showed lower stress levels that correlated only with speed performance.

To summarize, overall approach to hover data indicate the preferred visual symbology was BOSS and the preferred cueing display was TSAS with Aural ; these produced the best performance and were preferred over other symbologies and cueing conditions.

Hover

On average, the data indicate hover position performance was best with BOSS symbology (4.9 ft. from desired) over both Legacy (28.5 ft.) and FISH (14.4 ft.). This is likely to due to simplicity and intuitive attributes of BOSS symbology, specifically, the home plate symbol.

Heading maintenance data indicate performance with FISH was significantly better than Legacy, albeit by merely 1°. Supplemental aural and tactile cues significantly improved performance when utilizing FISH symbology.

Hover altitude performance data indicate BOSS was significantly better (by approximately 2 ft.) than both FISH and Legacy symbologies, probably due to the BOSS hover cue reference turning green when the desired altitude is achieved. This color change represents an additional perceptual cue to the pilot.

Biometric data failed to consistently correlate with flight performance or test pilot ratings for the Hover maneuver. Only GSR indicated lower workload/stress with BOSS symbology.

Overall, in the hover maneuver, the TSAS condition was ranked to be the easiest to fly (figure 18). The BOSS symbology was rated better than Legacy on all subjective scales. Additionally, the BOSS symbology was rated better than FISH on Cooper Harper, Bedford Workload Scale Workload, and the Vertical VCI.

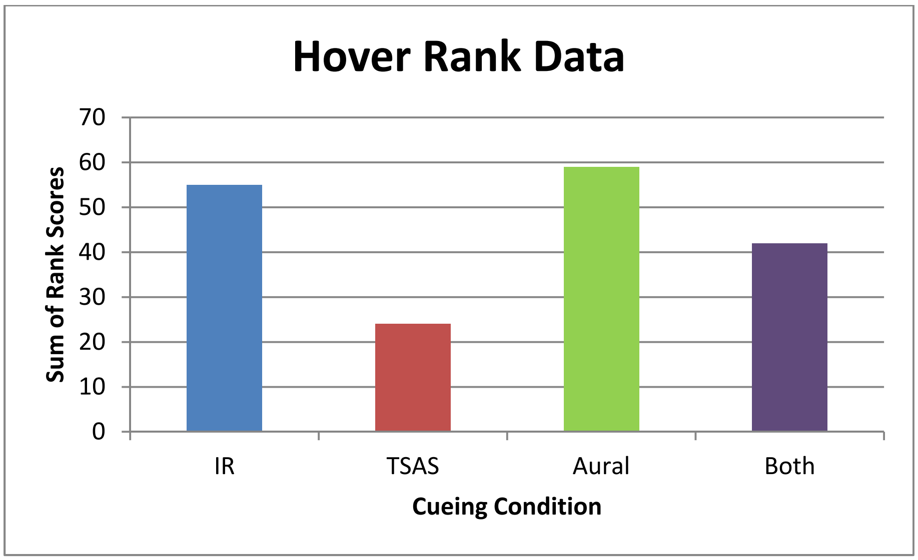


Figure 18. Sum of pilots' rank scores for hover. Note: "Both" refers to the combined TSAS and Aural display.

Sidestep

For the sidestep maneuver, the position deviation index data indicate performance was significantly worse with Legacy symbology (80 ft. from desired track) than both BOSS (12 ft.) and FISH (13 ft.) symbologies. This was believed to be principally due to the advanced features of the BOSS symbology (displaying a scaled velocity vector) and FISH symbology (via a slewable reposition capability). The data indicate FISH position maintenance was better with TSAS (likely due to the tactile cueing confirming the direction of the lateral sidestep maneuver) than with the Aural and TSAS and Aural cueing displays. Aural cueing during the sidestep maneuver appeared to be unnecessary and posed a distraction in the manner used in this test.

The data indicate performance with FISH symbology was better when paired with Aural than with TSAS. The speed data indicate when using Legacy symbology the sidestep velocity was faster when paired with TSAS cueing display rather than with the Aural or the TSAS and Aural cueing displays. This is likely due to high degree of pilot confidence associated with sensing tactile directional cues in the desired track.

Figure 19 shows the pilots' rank order of difficulty for the sidestep maneuver for each cueing display within each symbology set. Overall, the test pilots ranked the TSAS cueing display as the easiest to fly and the Aural cueing display as the most difficult.

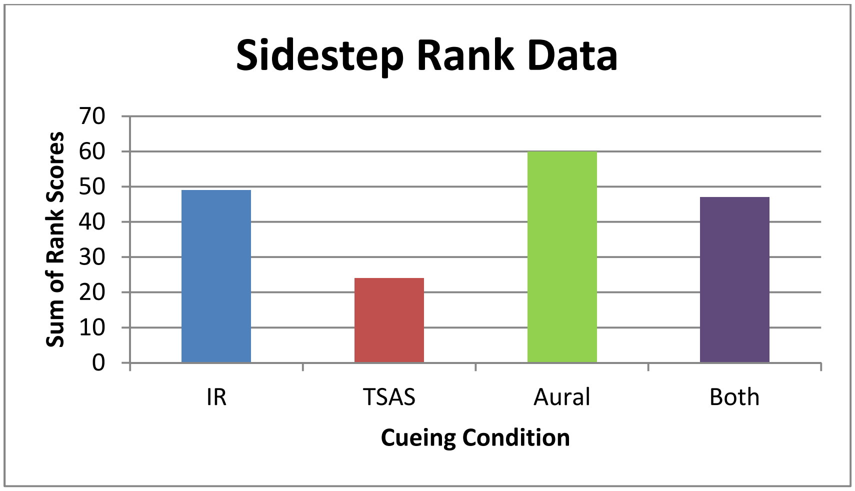


Figure 19. Sum of pilots' rank scores for sidestep. Note: "Both" refers to the combined TSAS and Aural display.

Biometric data failed to consistently predict performance or test pilot ratings, except that three of the four biometric measures correctly reflected test pilot preference for TSAS in the sidestep maneuver.

The data indicate that pilots rated BOSS over Legacy for all Visual Cue Indices. Additional cueing significance was found for the Horizontal VCI rating that suggests pilots preferred the Aural cueing display over the IR sensor image alone. Overall, in the sidestep maneuver the data suggest BOSS symbology and the TSAS cueing display were most effective.

Conclusions

To review, the goals of this project were to:

1) Determine if combining selected symbology/cueing sets would improve flight performance and/or reduce workload/stress.
2) Evaluate if the effectiveness of different combinations of the symbology/cueing sets would be reflected in test pilot subjective evaluations, flight performance, and workload/stress.
3) Determine if the effectiveness of different combinations of symbology/cueing sets would vary with the flight task.

In general, the results indicate that test pilot flight performance was improved when using advanced visual symbologies, particularly when combined with a supplemental form of cueing (aural and/or tactile). Advanced visual symbologies outperformed Legacy symbology for almost all maneuvers. BOSS symbology provided better overall performance compared to the FISH symbology, and BOSS symbology was the most preferred based on the subjective ratings for all maneuvers. These highly experienced test pilots reported that the BOSS symbology was simple to fly and provided them with spare cognitive capacity. Its features included an easily interpreted, positive affirmation of pilot control inputs by providing a color change (green fill) on the vertical and horizontal velocity indicators to indicate maneuver accuracy. The test pilots reported this function provided increased awareness of performance and assisted with recoveries from flight deviations.

The optimal cueing display was dependent on the maneuver and the type of visual symbology being used. The results indicated that the combined TSAS and Aural cueing display provided the best synergy for the approach to landing and approach to hover maneuvers, while the TSAS cueing display was the optimal supplemental cue for the hover and sidestep maneuvers. Rank data indicated that the test pilots expressed an overall preference for the TSAS cueing display, followed by the TSAS and Aural cueing display. The Aural cueing display (without TSAS), as implemented in this study, was ranked as the most difficult to fly. The test pilots reported that they preferred the aural cues that provided situational information, such as the "assume guidance" and altitude countdown cues, over aural cues that demanded corrective action to satisfy a required performance measure. Their opinion was that excessive aural cues, particularly those that demanded corrective action, were annoying and had the potential to distract and possibly degrade flight performance (comments supported by the biometric monitoring data). When aural cues were paired with the FISH and Legacy symbologies, test observers witnessed an increase in test pilot induced oscillations. According to the test pilots, the pilot-induced oscillations occurring when using the FISH symbology and aural cues were the result of the visual symbology being "overly" sensitive and the aural cues providing insufficient information.

The results of the biometric data failed to consistently correlate with flight performance or test pilot workload ratings or cueing preferences. Mean respiratory interval data revealed that for the Legacy symbology, TSAS was preferred over Legacy without supplemental cueing. GSR results indicate that the Legacy symbology with aural cueing was indicative of increased stress over BOSS with TSAS, BOSS with Aural, and all FISH conditions. The biometric measures may reflect aspects of workload and performance that are not fully understood. At this point, conclusions based on these biometric parameters would be premature.

Recommendations

If a project management decision is anticipated based on these results, it is recommended that future tests in this program include BOSS with 3D conformal symbology and sensor imagery. If proprietary restrictions permit, BOSS symbology should incorporate both the FISH enroute page attributes, and the FISH sidestep slewing capabilities. BOSS symbology should be paired with TSAS and modified aural cues for all maneuvers. TSAS modes should include a precision approach mode and threat cues. Aural cues should provide altitude information and indicate mode changes.

Further exploration of biometric stress measures is suggested to provide baseline data for future flight tests and to determine which measures provide the most robust data in dynamic flight environments. To reduce the noise in the GSR data caused by hand movements, it is recommended that alternate electrode placements be explored.

This page is intentionally left blank.

References

Allan, K., White, T., Jones, L., Merlo, J., Haas, E., Zets, G., et al. (2010). Getting the buzz: What's next for tacile information delivery? *Preceedings of the Human Factors and Ergonomics Society Annual Meeting 2010*, 1331-1334.

Colucci, F. (2007, Spring). Digging out from brownout. *Vertiflite*, pp. 50-55.

Cox, J. (2014). *Preliminary Utility Assessment of the Tactile Situational Awareness System.* Flight Test Branch.

Craig, G., Jennings, S., Cheung, B., Rupert, A., and Schultz, K. (2008). Flight-test of a tactile situational awareness system in a land-based deck landing task. *Proceedings of the Human Factors and Ergonomics Society*, 142-146.

Curtis, M. T., Jentsch, F., and Wise, J. (2010). Aviation Displays. In E. Salas, & D. Maurino, *Human Factors in Aviation* (2nd ed., p. 453). Burlington: Elsevier.

Dehais, F., Causse, M., Vachon, F., Regis, N., Menant, E., & Tremblay, S. (2014). Failure to detect critical auditory alerts in the cockpit: Evidence for inatentional deafness. *Human Factors and Ergonomics Society*, 631-644.

Elliott, L., Coovert, M., Prewett, M., Walvord, A., Saboe, K., and Johnson, R. (2009). *A review and meta analysis of vibrotactile and visual information displays.* Aberdeen Proving Ground: Army Research Laboratory.

Elliott, L., Schmeisser, E., and Redden, E. (2011). *Development of tactile and haptic systems for U.S. infantry navigation and communication.* Fort Benning, GA: US Army Reserach Lab, Human Research and Engineering Directorate.

Holmes, N. (2009). The principle of inverse effectiveness in multisensory integration: some statistical considerations. *Brain Topograpy, 21*, 168-176.

Jones, L., and Sarter, N. (2008). Tactile displays: Guidance for their design and application. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 90-111.

Kenny, C. W., and Wei, C. L. (2009). Association testing - A methodology for selecting and evaluating audio alerts. *Preceedings of the Human Factors and Ergonomics Society Annual Meeting*, 53-59.

Lawson, B. D., and Rupert, A. H. (2014). *Coalition Warfare Program Tactile Situation Awareness System for Aviation Applicatoins: Systems Development.* Fort Rucker: USAARL Warfighter Health Division.

Lu, S., Wickens, C. D., Sarter, N. B., and Sebok, A. (2011). Informing the design of multimodal displays: A meta-analysis of Empirical studies comparing auditory and tactile interruptions. *Proceedings of the Human Factors and Ergonomics Society 55th Annual Meeting*, 1170-1174.

Mateo, J., Simpson, B., Gilkey, B., Iyer, N., and Brungart, D. (2012). Spatial multisensory cueing to support visual target-acquisition performance. *Proceedings of the Human Factors and Ergonomics Society 56th Annual Meeting*, 1312-1316.

McGrath, B., Estrada, A., Braithwaite, M., Raj, A., and Rupert, A. (2004). *Tactile situational awareness system flight demonstration final report.* f: USAARL.

Mejdal, S., McCauley, M., and Beringer, D. B. (2001). *Human factors guidelines for muiltifunctin displays.* Washington, D.C.: FAA.

Moralez, E., Shively, R. J., Grumwald, A. J., and Hovev, M. (2011). Forward-looking integrated symbology for 4-D reroutable helicopter approach-to-landing. *American Helicopter Society 66th Annual Forum*.

North Atlantic Treaty Organization [NATO] Task Group HFM-162. (2012). *Rotary-wing brownout mitigation technology and training.* RTO/NATO.

Sanders, M., and McCormick, E. (1993). *Human Factors in Engineering Desing.* New York: McGraw-Hill, Inc.

Sarter, N. (2007). Multiple resource theory as a bases for mutlimodal interface design: Success stories, qualifications, and research needs. In A. F. Kramer, D. Weigmann, & A. Kirlik, *Attention: From Theory to Practice.* New York: Oxford Publishing.

Sklar, A., and Sarter, N. (1999). Good vibrations: Tactile feedback in support of attential allocations and human-automation coordination in event-driven domains. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 543-552.

Stokes, A., and Wickens, C. (1988). Aviation Displays. In E. Wiener, & D. Nagel, *Human Factors in Aviation* (p. 403). San Diego: Academic Press.

Szoboszlay, Z. P., Turpin, T. S., and McKinley, R. A. (2009). Symbology for Brown-Out Landings: The First Simulation for the 3D-LZ Program. *In proceeding of: American Helicopter Society 65th Annual Forum.*

Thompson, B. (2011, 09 08). *Symbology Collaboration Helps Pilots "See" During Brownouts.* Retrieved from Wright-Patterson Air Force Base: http://www.wpafb.af.mil/news/story.asp?id=123271120

Veltman, J. A., Oving, A. B., and Bronkhorst, A. W. (2009). 3-D audio in the fighter cockpit improves task performance. *The International Journal of Aviation Pyschology, 14*(3), 239-256.

Vidulick, M., Wickens, C., Tsang, P., and Flach, J. (2010). Information Processing in Aviation. In E. Salas, & D. Maurina, *Human Factors in Aviation* (pp. 175-207). Burlington: Elsevier.

Whittle, R. (2012, 03 09). *Army seeks brownout fixes for helo pilots, Afghan tests loom*. Retrieved from Breaking Defense: http://breakingdefense.com/2012/03/army-seeks-brownout-fixes-for-helo-pilots-afghan-tests-loom/

Wickens, C. (2003). Aviation Displays. In P. Tsang, and M. Vudilich, *Principles and Practice of Aviation Psychology* (pp. 147-200). Mahwah, Ney Jersey: Lawrence Erlbaum Associates.

This page is intentionally left blank.

Appendix A.

Flight performance and subjective results.

Table A-1.
Mean deviations by symbology and significance values between symbology sets for Approach to Landing maneuver.

Approach to Landing	**Mean**			***p*-value (*p* < .05)**		
Index	Legacy	BOSS	FISH	Legacy/ BOSS	Legacy/ FISH	FISH/ BOSS
Position(feet)	22.683	9.823	15.465	<0.001	0.075	0.151
Heading (degrees)	3.656	2.661	3.900	0.001	0.960	<0.001
Altitude (feet)	9.849	8.816	7.967	0.270	0.007	0.381
Speed (knots)	9.946	6.703	8.184	0.003	0.271	0.225

Table A-2.
Cueing mean deviations and significance values for Approach to Landing maneuver.

Approach to Landing	**Mean Deviation**				***p*-value (*p* < .05)**					
Measure	IR	TSAS	Aural	Both*	IR/ TSAS	IR/ Aural	IR/ Both*	TSAS/ Aural	TSAS/ Both*	Aural/ Both*
Position (feet)										
Legacy (Distance at Touchdown)	17.231	20.019	29.064	24.419	0.493	0.138	0.675	0.333	0.947	0.254
BOSS (Distance at Touchdown)	10.270	8.163	6.941	13.920	0.030	0.048	0.347	0.734	0.439	0.443
FISH (Distance at Touchdown)	24.632	13.476	6.961	16.789	0.612	0.135	0.467	0.085	0.968	0.276
Heading (degrees)										
Legacy (Level Phase SD)	0.750	0.534	0.888	0.353	0.229	0.672	0.144	0.183	0.949	0.045
BOSS (Level Phase SD)	0.253	0.415	0.361	0.282	0.362	0.667	0.970	0.659	0.362	0.531
FISH (Level Phase SD)	0.848	0.886	1.214	1.062	0.953	0.135	0.601	0.179	0.704	0.332
Legacy (Transition to Approach SD)	0.828	0.446	0.803	0.755	0.413	0.978	0.888	0.472	0.366	0.891
BOSS (Transition to Approach SD)	0.417	0.464	0.441	0.280	0.665	0.944	0.304	0.618	0.157	0.151
FISH (Transition to Approach SD)	1.154	0.612	1.352	1.183	0.189	0.828	0.628	0.117	0.423	0.408
Legacy (Approach SD)	1.060	0.833	0.762	0.956	0.443	0.254	0.822	0.199	0.373	0.164

Table A-2 (continued).

Approach to Landing	Mean Deviation				*p*-value ($p < .05$)					
Measure	IR	TSAS	Aural	Both*	IR/ TSAS	IR/ Aural	IR/ Both*	TSAS/ Aural	TSAS/ Both*	Aural/ Both*
Heading (degrees)										
BOSS (Approach SD)	1.000	0.813	0.732	0.935	0.480	0.278	0.737	0.341	0.409	0.216
FISH (Approach SD)	1.164	1.267	1.239	1.382	0.675	0.964	0.235	0.598	0.486	0.343
Legacy (Transition to Touchdown SD)	1.300	1.696	1.261	1.401	0.197	0.813	0.975	0.340	0.497	0.768
BOSS (Transition to Touchdown SD)	0.782	1.335	0.870	1.261	0.121	0.431	0.332	0.162	0.202	0.523
FISH (Transition to Touchdown SD)	0.489	0.547	0.614	0.591	0.852	0.835	0.251	0.711	0.274	0.642
Altitude (feet)										
Legacy (Level Phase RMSD)	9.468	10.609	10.150	9.168	0.324	0.541	0.876	0.752	0.157	0.518
BOSS (Level Phase RMSD)	8.860	9.218	8.681	8.503	0.545	0.888	0.851	0.490	0.330	0.926
FISH (Level Phase RMSD)	8.001	7.017	7.756	9.093	0.226	0.659	0.447	0.438	0.100	0.314
Speed (knots)										
Legacy (Level Phase RMSD)	0.391	0.586	1.361	0.829	0.522	0.017	0.404	0.096	0.607	0.054
BOSS (Level Phase RMSD)	1.085	1.691	1.070	0.728	0.389	0.416	0.127	0.065	0.119	0.745
FISH (Level Phase RMSD)	0.919	1.140	1.112	1.632	0.844	0.724	0.129	0.860	0.061	0.278
Legacy (Approach RMSD)	8.510	6.521	7.369	6.888	0.322	0.449	0.389	0.616	0.738	0.763
BOSS (Approach RMSD)	5.149	5.366	4.916	5.640	0.665	0.982	0.569	0.593	0.833	0.464
FISH (Approach RMSD)	5.302	4.190	4.713	4.442	0.398	0.893	0.708	0.524	0.777	0.736
Legacy (Landing)	3.234	2.655	3.863	2.551	0.279	0.538	0.215	0.048	0.961	0.237
BOSS (Landing)	1.541	1.532	1.173	2.052	0.580	0.472	0.227	0.970	0.061	0.075
FISH (Landing)	3.759	3.209	2.507	4.684	0.345	0.124	0.841	0.543	0.277	0.101

Table A-2 (continued).

Approach to Landing	**Mean Deviation**				***p*-value (*p* < .05)**					
Measure	IR	TSAS	Aural	Both*	IR/ TSAS	IR/ Aural	IR/ Both*	TSAS/ Aural	TSAS/ Both*	Aural/ Both*
Speed (knots)										
Legacy (Landing Lateral Drift)	0.322	0.414	0.161	0.127	0.375	0.070	0.046	0.048	0.060	0.305
BOSS (Landing Lateral Drift)	0.279	0.170	0.342	0.078	0.648	0.257	0.382	0.130	0.092	0.815
FISH (Landing Lateral Drift)	0.325	0.308	0.212	0.282	0.949	0.342	0.986	0.259	0.938	0.457

* "Both" refers to the combined TSAS and Aural display.

Table A-3.
Summary of subjective data for symbology for Approach to Landing maneuver.

Approach to Landing	**Mean**			***p*-value (*p* < .05)**		
Measure	Legacy	BOSS	FISH	Legacy/ BOSS	Legacy/ FISH	FISH/ BOSS
Cooper Harper	4.6988	3.438	4.250	0.042	0.484	0.078
Bedford	5.250	3.938	4.781	0.035	0.401	0.046
VCI Attitude	3.802	2.530	2.771	0.028	0.123	0.398
VCI Horizontal	3.438	2.000	2.688	0.017	0.123	0.207
VCI Vertical	3.594	1.656	2.500	0.017	0.068	0.061

Table A-4.
Summary of subjective data for cueing for Approach to Landing maneuver.

Approach to Landing	**Mean**				***p*-value (*p* < .05)**					
Measure	IR	TSAS	Aural	Both*	IR/ TSAS	IR/ Aural	IR/ Both*	TSAS/ Aural	TSAS/ Both*	Aural/ Both*
Cooper Harper	4.167	3.958	4.167	4.208	0.279	0.739	0.916	0.157	0.168	0.785
Bedford	4.625	4.667	4.833	4.500	0.932	0.445	0.581	0.493	0.216	0.024
VCI Attitude	2.985	3.014	3.041	3.097	0.916	0.715	0.174	1.000	0.500	0.344
VCI Horizontal	2.792	2.542	2.667	2.833	0.344	0.414	0.916	0.593	0.670	0.458
VCI Vertical	2.625	2.625	2.500	2.583	0.932	0.680	0.730	0.673	0.655	0.786

* "Both" refers to the combined TSAS and Aural display.

Table A-5.
Mean deviations by symbology and significance values between symbology sets for Approach to Hover maneuver.

Approach to Hover	**Mean**			***p*-value (*p* < .05)**		
Index	Legacy	BOSS	FISH	Legacy/ BOSS	Legacy/ FISH	FISH/ BOSS
Position(feet)	50.904	9.681	33.963	<0.001	0.006	<0.001
Heading (degrees)	6.914	5.282	6.626	0.080	1.000	0.066
Altitude (feet)	19.965	9.525	10.698	<0.001	<0.001	0.200
Speed (knots)	7.836	6.132	5.364	0.150	0.003	0.408

Table A-6.
Cueing mean deviations and significance values for Approach to Hover maneuver.

Approach to Hover	**Mean Deviation**				***p*-value (*p* < .05)**					
Measure	IR	TSAS	Aural	Both*	IR/ TSAS	IR/ Aural	IR/ Both*	TSAS/ Aural	TSAS/ Both*	Aural/ Both*
Position (feet)										
Legacy (Lateral Hover Position RMSD)	7.296	9.346	9.865	7.568	0.780	0.915	0.610	0.597	0.994	0.687
BOSS (Lateral Hover Position RMSD)	2.214	2.377	2.427	4.706	0.832	0.538	0.057	0.837	0.087	0.205
FISH (Lateral Hover Position RMSD)	1.990	2.142	2.144	2.832	0.845	0.985	0.347	0.834	0.197	0.211
Legacy (Longitudinal Hover Position RMSD)	42.870	33.194	34.107	59.372	0.877	0.618	0.471	0.502	0.521	0.295
BOSS* (Longitudinal Hover Position RMSD)	3.980	11.796*	6.526	4.697	0.012	0.105	0.562	0.426	0.137	0.669
FISH (Longitudinal Hover Position RMSD)	34.169	31.710	42.445	18.311	0.093	0.401	0.248	0.788	0.785	0.663
Heading (degrees)										
Legacy (Level Phase SD)	0.561	0.669	0.693	0.670	0.946	0.274	0.649	0.444	0.711	0.439
BOSS (Level Phase SD)	0.604	0.317	0.328	0.285	0.393	0.126	0.281	0.485	0.582	0.770
FISH (Level Phase SD)	1.448	1.329	1.072	0.851	0.819	0.141	0.012	0.271	0.028	0.289

Table A-6 (continued).

Approach to Hover	Mean Deviation				*p*-value (p < .05)					
Measure	IR	TSAS	Aural	Both*	IR/ TSAS	IR/ Aural	IR/ Both*	TSAS/ Aural	TSAS/ Both*	Aural/ Both*
Heading (degrees)										
Legacy (Transition to Approach SD)	0.862	0.842	0.563	0.895	0.416	0.103	0.307	0.544	0.800	0.903
BOSS (Transition to Approach SD)	0.815	0.425	0.467	0.478	0.299	0.318	0.125	0.624	0.725	0.976
FISH (Transition to Approach SD)	0.932	1.267	0.979	0.700	0.694	0.409	0.230	0.319	0.180	0.782
Legacy (Approach SD)	0.962	0.888	0.805	0.848	0.662	0.646	0.799	0.923	0.713	0.763
BOSS (Approach SD)	0.834	1.055	0.798	0.894	0.363	0.762	0.974	0.062	0.162	0.529
FISH (Approach SD)	0.870	1.171	1.047	1.146	0.209	0.463	0.315	0.929	0.952	0.966
Legacy (Transition to Hover SD)	1.645	1.588	1.488	1.673	0.638	0.495	0.786	0.991	0.792	0.749
BOSS (Transition to Hover SD)	1.130	1.420	0.963	0.946	0.224	0.429	0.291	0.137	0.031	0.889
FISH (Transition to Hover SD)	1.004	0.744	0.939	1.054	0.166	0.782	0.668	0.090	0.060	0.456
Legacy (Hover RMSD)	2.579	3.426	3.383	2.617	0.233	0.176	0.894	0.867	0.204	0.167
BOSS (Hover RMSD)	2.054	2.701	1.981	2.635	0.321	0.423	0.896	0.074	0.409	0.465
FISH (Hover RMSD)	2.895	2.406	2.190	2.459	0.718	0.388	0.366	0.617	0.737	0.831
Altitude (feet)										
Legacy (Level Phase RMSD)	9.745	9.004	11.343	9.235	0.842	0.519	0.937	0.259	0.854	0.294
BOSS (Level Phase RMSD)	7.363	7.441	8.291	9.195	0.921	0.410	0.033	0.481	0.128	0.413
FISH (Level Phase RMSD)	7.003	7.672	7.060	6.734	0.523	0.990	0.955	0.568	0.446	0.951
Legacy (Hover RMSD)	10.340	8.541	10.516	11.136	0.217	0.772	0.777	0.373	0.584	0.981
BOSS (Hover RMSD)	1.790	1.216	1.554	1.249	0.012	0.392	0.143	0.630	0.703	0.821
FISH (Hover RMSD)	3.693	3.797	3.839	2.992	0.761	0.805	0.320	0.664	0.202	0.518

Table A-6 (continued).

Approach to Hover	**Mean Deviation**				***p*-value (*p* < .05)**					
Measure	IR	TSAS	Aural	Both*	IR/ TSAS	IR/ Aural	IR/ Both*	TSAS/ Aural	TSAS/ Both*	Aural/ Both*
Speed (knots)										
Legacy (Level Phase RMSD)	0.886	0.753	1.316	0.889	0.546	0.311	0.942	0.060	0.342	0.121
BOSS (Level Phase RMSD)	0.998	1.249	1.008	0.946	0.319	0.920	0.652	0.321	0.249	0.760
FISH* (Level Phase RMSD)	0.744	1.664*	0.756	0.879	0.100	0.825	0.337	0.036	0.313	0.459
Legacy (Approach RMSD)	5.401	6.472	8.656	6.971	0.269	0.035	0.543	0.303	0.982	0.423
BOSS (Approach RMSD)	5.061	5.522	4.567	5.175	0.815	0.636	0.551	0.362	0.933	0.267
FISH (Approach RMSD)	4.318	4.483	4.302	4.310	0.327	0.470	0.834	0.214	0.605	0.839

* “Both” refers to the combined TSAS and Aural display.

Table A-7.
Summary of subjective data for symbology for Approach to Hover maneuver.

Approach to Hover	**Mean**			***p*-value (*p* < .05)**		
Measure	Legacy	BOSS	FISH	Legacy/ BOSS	Legacy/ FISH	FISH/ BOSS
Cooper Harper	5.5313	3.9063	4.6250	0.017	0.324	0.233
Bedford	5.5938	4.2188	5.1563	0.020	0.445	0.128
VCI Attitude	3.9478	2.4991	2.7706	0.012	0.068	0.208
VCI Horizontal	3.5625	2.0313	2.5938	0.018	0.079	0.293
VCI Vertical	3.7188	1.7813	2.5313	0.018	0.021	0.108

Table A-8.
Summary of subjective data for cueing Approach to Hover maneuver.

Approach to Hover	**Mean**				***p*-value (*p* < .05)**					
Measure	IR	TSAS	Aural	Both*	IR/ TSAS	IR/ Aural	IR/ Both*	TSAS/ Aural	TSAS/ Both*	Aural/ Both*
Cooper Harper	4.542	4.708	4.750	4.750	0.233	0.246	0.395	1.000	0.861	0.863
Bedford	4.875	5.000	5.125	4.958	0.680	0.306	0.524	0.621	0.832	0.416
VCI Attitude	3.166	3.124	3.028	2.972	0.674	0.345	0.075	0.462	0.248	0.893
VCI Horizontal	2.750	2.708	2.792	2.667	1.000	0.705	0.453	0.581	0.609	0.340
VCI Vertical	2.708	2.750	2.583	2.667	0.865	0.343	0.734	0.496	0.414	0.719

* “Both” refers to the combined TSAS and Aural display.

Table A-9.
Mean deviations by symbology and significance values between symbology sets for Hover maneuver.

Hover	**Mean**			***p*-value (p < .05)**		
Index	Legacy	BOSS	FISH	Legacy/ BOSS	Legacy/ FISH	FISH/ BOSS
Position(feet)	28.447	4.896	14.357	<0.001	<0.001	<0.001
Heading (degrees)	2.028	1.891	1.017	0.595	0.024	0.312
Altitude (feet)	3.576	1.062	3.019	<0.001	0.231	<0.001

Table A-10.
Cueing mean deviations and significance values for Hover maneuver.

Hover	**Mean Deviation**				***p*-value (*p* < .05)**					
Measure	IR	TSAS	Aural	Both*	IR/ TSAS	IR/ Aural	IR/ Both*	TSAS/ Aural	TSAS/ Both*	Aural/ Both*
Position (feet)										
Legacy (Lateral Hover Position RMSD)	6.353	6.646	5.958	5.819	0.786	0.396	0.414	0.722	0.519	0.968
BOSS (Lateral Hover Position RMSD)	1.335	1.533	1.432	2.481	0.452	0.710	0.531	0.687	0.810	0.677
FISH (Lateral Hover Position RMSD)	1.644	1.878	1.543	2.069	0.260	0.950	0.478	0.200	0.925	0.494
Legacy (Longitudinal Hover Position RMSD)	20.989	25.780	23.858	18.383	0.327	0.473	0.685	0.519	0.103	0.061
BOSS (Longitudinal Hover Position RMSD)	2.620	3.547	3.324	3.311	0.941	0.993	1.000	0.943	0.940	0.994
FISH (Longitudinal Hover Position RMSD)	12.056	10.917	11.363	15.959	0.778	0.872	0.586	0.940	0.699	0.643
Heading (degrees)										
Legacy (Hover RMSD)	2.381	2.063	1.917	1.749	0.907	0.573	0.729	0.809	0.793	0.896
BOSS (Hover RMSD)	1.467	2.289	1.499	2.308	0.662	0.633	0.928	0.223	0.679	0.839
FISH* (Hover RMSD)	0.944	0.834	0.753	1.535*	0.587	0.215	0.661	0.251	0.385	0.026
Altitude (feet)										
Legacy (Hover RMSD)	3.787	3.644	3.288	3.586	0.945	0.912	0.840	0.794	0.949	0.720
BOSS (Hover RMSD)	1.173	1.027	1.049	0.998	0.481	0.774	0.695	0.525	0.970	0.657
FISH (Hover RMSD)	2.652	2.907	2.819	3.698	0.790	0.898	0.199	0.939	0.422	0.134

* “Both” refers to the combined TSAS and Aural display.

Table A-11.
Summary of subjective data for symbology for Hover maneuver.

Hover	**Mean**			***p*-value (*p* < .05)**		
Measure	Legacy	BOSS	FISH	Legacy/ BOSS	Legacy/ FISH	FISH/ BOSS
Cooper Harper	5.1875	3.5313	4.562	0.018	0.398	0.042
Bedford	5.3125	3.7188	5.0313	0.020	0.779	0.027
VCI Attitude	3.6878	2.2497	2.7288	0.012	0.161	0.205
VCI Horizontal	3.1875	1.9375	2.5938	0.012	0.293	0.125
VCI Vertical	3.500	1.5938	2.5625	0.012	0.074	0.017

Table A-12.
Summary of subjective data for cueing for Hover maneuver.

Hover	**Mean**				***p*-value (*p* < .05)**					
Measure	IR	TSAS	Aural	Both*	IR/ TSAS	IR/ Aural	IR/ Both*	TSAS/ Aural	TSAS/ Both*	Aural/ Both*
Cooper Harper	4.375	4.417	4.458	4.458	0.915	0.724	0.500	0.670	0.734	1.000
Bedford	4.625	4.750	4.750	4.625	0.596	0.490	0.799	0.932	0.609	0.395
VCI Attitude	2.958	2.972	2.820	2.806	0.888	0.483	0.528	0.248	0.397	0.893
VCI Horizontal	2.583	2.500	2.708	2.500	0.492	0.496	0.751	0.059	0.715	0.344
VCI Vertical	2.583	2.667	2.500	2.458	0.495	0.526	0.778	0.553	0.339	0.786

* “Both” refers to the combined TSAS and Aural display.

Table A-13.
Mean deviations by symbology and significance values between symbology sets for Sidestep maneuver.

Sidestep	**Mean**			***p*-value (*p* < .05)**		
Index	Legacy	BOSS	FISH	Legacy/ BOSS	Legacy/ FISH	FISH/ BOSS
Position(feet)	80.340	12.160	13.015	<0.001	<0.001	0.763
Heading (degrees)	1.991	1.895	0.989	1.000	0.078	0.069
Altitude (feet)	7.035	5.035	5.280	0.642	0.854	0.981
Speed (knots)	5.066	5.640	3.987	<0.001	<0.001	<0.001

Table A-14.
Cueing mean deviations and significance values for Sidestep maneuver.

Sidestep	**Mean Deviation**				***p*-value (*p* < .05)**					
Measure	IR	TSAS	Aural	Both*	IR/ TSAS	IR/ Aural	IR/ Both*	TSAS/ Aural	TSAS/ Both*	Aural/ Both*
Position (feet)										
Legacy (Lateral Position RMSD)	78.442	75.674	81.210	86.034	0.847	0.552	0.334	0.452	0.231	0.261
BOSS (Lateral Position RMSD)	11.883	12.686	10.648	13.423	0.855	0.619	0.757	0.776	0.712	0.519
FISH (Lateral Position RMSD)	10.064	6.695	13.122	22.180	0.134	0.225	0.019	0.017	0.011	0.305
Heading (degrees)										
Legacy (Sidestep RMSD)	2.047	1.892	1.796	2.230	0.639	0.850	0.723	0.636	0.838	0.781
BOSS (Sidestep RMSD)	1.335	2.240	1.739	2.267	0.407	0.386	0.838	0.889	0.787	0.835
FISH (Sidestep RMSD)	0.838	1.157	0.806	1.154	0.258	0.131	0.488	0.017	0.635	0.074
Altitude (feet)										
Legacy (Maximum Altitude)	33.685	34.234	33.443	33.659	0.916	0.805	0.869	0.834	0.869	0.941
BOSS (Maximum Altitude)	33.778	33.132	33.865	32.591	0.483	0.833	0.201	0.398	0.304	0.108
FISH (Maximum Altitude)	31.345	32.235	31.792	33.217	0.325	0.545	0.366	0.721	0.682	0.481
Legacy (Minimum Altitude)	26.379	27.423	27.902	25.179	0.187	0.202	0.393	0.783	0.171	0.709
BOSS (Minimum Altitude)	28.572	27.036	28.456	29.161	0.294	0.960	0.488	0.325	0.191	0.341
FISH (Minimum Altitude)	26.687	25.896	26.983	27.904	0.553	0.828	0.243	0.471	0.258	0.591
Speed (knots)										
Legacy (Maximum Velocity)	5.040	5.352	4.988	4.885	0.133	0.832	0.150	0.010	0.013	0.506
BOSS (Maximum Velocity)	5.645	5.651	5.853	5.411	0.973	0.421	0.401	0.246	0.537	0.064
FISH (Maximum Velocity)	3.939	3.948	3.853	4.206	0.963	0.312	0.285	0.181	0.404	0.237

* “Both” refers to the combined TSAS and Aural display.

Table A-15.
Summary of subjective data for symbology for Sidestep maneuver.

Sidestep	**Mean**			***p*-value (*p* < .05)**		
Measure	Legacy	BOSS	FISH	Legacy/ BOSS	Legacy/ FISH	FISH/ BOSS
Cooper Harper	4.969	4.156	4.313	0.079	0.395	0.799
Bedford	5.375	4.500	4.969	0.079	0.528	0.181
VCI Attitude	3.740	2.614	2.646	0.012	0.123	0.499
VCI Horizontal	3.063	2.063	2.344	0.011	0.233	0.671
VCI Vertical	3.469	2.031	2.531	0.017	0.150	0.105

Table A-16.
Summary of subjective data for cueing for Sidestep maneuver.

Sidestep	**Mean**				***p*-value (*p* < .05)**					
Measure	IR	TSAS	Aural	Both*	IR/ TSAS	IR/ Aural	IR/ Both*	TSAS/ Aural	TSAS/ Both*	Aural/ Both*
Cooper Harper	4.417	4.500	4.583	4.417	0.750	0.157	0.596	0.730	0.609	0.465
Bedford	4.958	4.958	4.875	5.000	0.684	0.497	0.865	0.458	0.932	0.339
VCI Attitude	3.069	3.028	2.903	3.000	0.917	0.352	0.575	0.465	0.854	0.465
VCI Horizontal	2.667	2.500	2.333	2.458	0.244	0.027	0.064	0.180	0.496	0.461
VCI Vertical	2.792	2.667	2.583	2.667	0.480	0.344	0.553	1.000	1.000	0.726

* “Both” refers to the combined TSAS and Aural display.

Appendix B.

Questionnaire

Subject #: Date:

Flight hours experience

Total flight hours: ______
UH-60 _______
NVS (FLIRs) ______
NVG: _____

Pilot in Command: _______
Other Rotary_________
Other aircraft _________

Experience with cueing technologies: (hours)

Legacy HUD :________ FISH: ________
BOSS: ________ TSAS: ________ Aural Cueing Products: __________

Task Difficulty Ranking

1. Please rank order the difficulty of the three different maneuvers performed while using the multifunctional display with visual symbology, haptic cues, and aural cues, where 1 is the least difficult and 4 is the most difficult. Thus, each column will rank order the difficulty of the three flight tasks for that column's symbology/cue set. (circle one in each category)

Category	Approach and Landing	Hover	Sidestep
Legacy HUD	1 2 3 4	1 2 3 4	1 2 3 4
Legacy + Haptic	1 2 3 4	1 2 3 4	1 2 3 4
Legacy + Aural	1 2 3 4	1 2 3 4	1 2 3 4
Legacy + Aural + Haptic	1 2 3 4	1 2 3 4	1 2 3 4

Category	Approach and Landing	Hover	Sidestep
BOSS	1 2 3 4	1 2 3 4	1 2 3 4
BOSS + Haptic	1 2 3 4	1 2 3 4	1 2 3 4
BOSS + Aural	1 2 3 4	1 2 3 4	1 2 3 4
BOSS + Aural + Haptic	1 2 3 4	1 2 3 4	1 2 3 4

Category	Approach and Landing	Hover	Sidestep
FISH	1 2 3 4	1 2 3 4	1 2 3 4
Fish + Haptic	1 2 3 4	1 2 3 4	1 2 3 4
FISH + Aural	1 2 3 4	1 2 3 4	1 2 3 4
FISH + Aural + Haptic	1 2 3 4	1 2 3 4	1 2 3 4

2. What *visual* symbology indications do you feel are necessary on the multifunction display in order to successfully conduct the test maneuvers (check all that apply)?

___ Airspeed ___ Vertical Speed
___ Attitude ___ Velocity Vector ___ Torque
___ Heading ___ Turn & Slip ___ Altimeter

3. What advanced cueing indications do you feel are beneficial in order to adequately conduct all test maneuvers (check all that apply)?

Haptic:

___ Airspeed ___ Vertical Speed
___ Attitude ___ Velocity Vector ___ Torque
___ Heading ___ Turn & Slip _ _ Altitude

Aural:

___ Airspeed ___ Vertical Speed
___ Attitude ___ Velocity Vector ___ Torque
___ Heading ___ Turn & Slip ___ Altitude

4. What other combinations of cueing technologies would you desire to see implemented in the future? (Please describe below)

Thank you for your time and service.

Appendix C.

Outlier charts.

Approach to landing

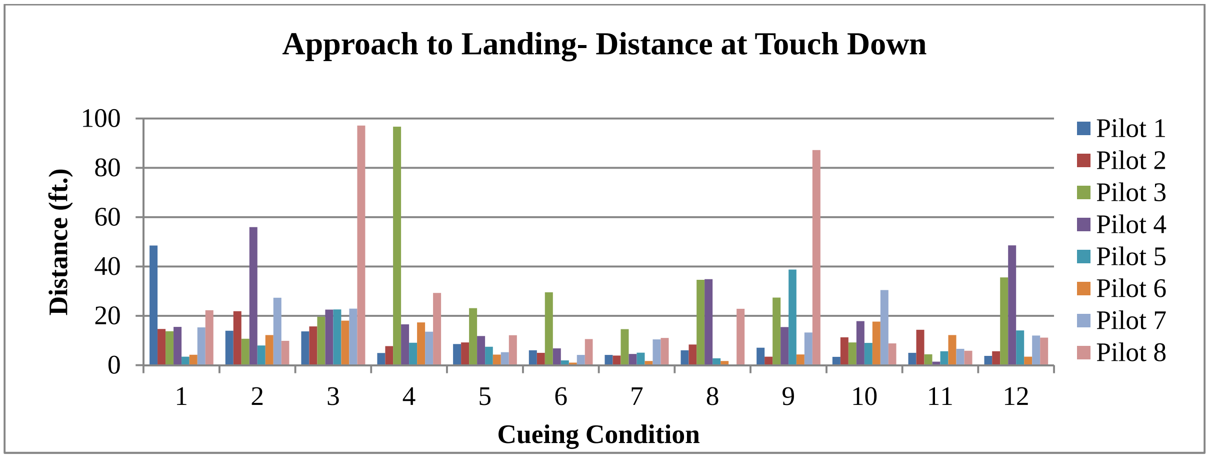


Figure C-1. Approach to Landing- Distance at Touch Down.

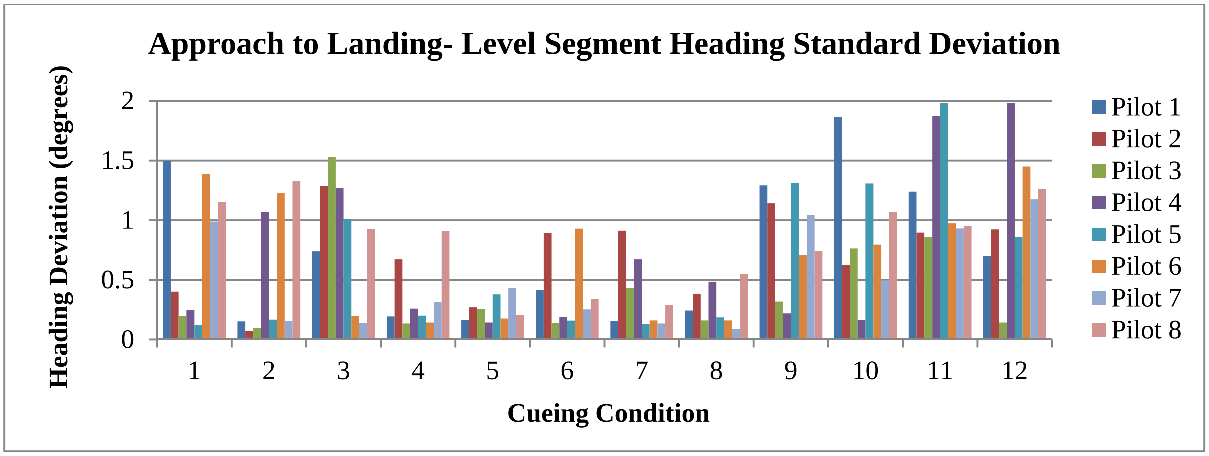


Figure C-2. Approach to Landing- Level Segment Heading Standard Deviation.

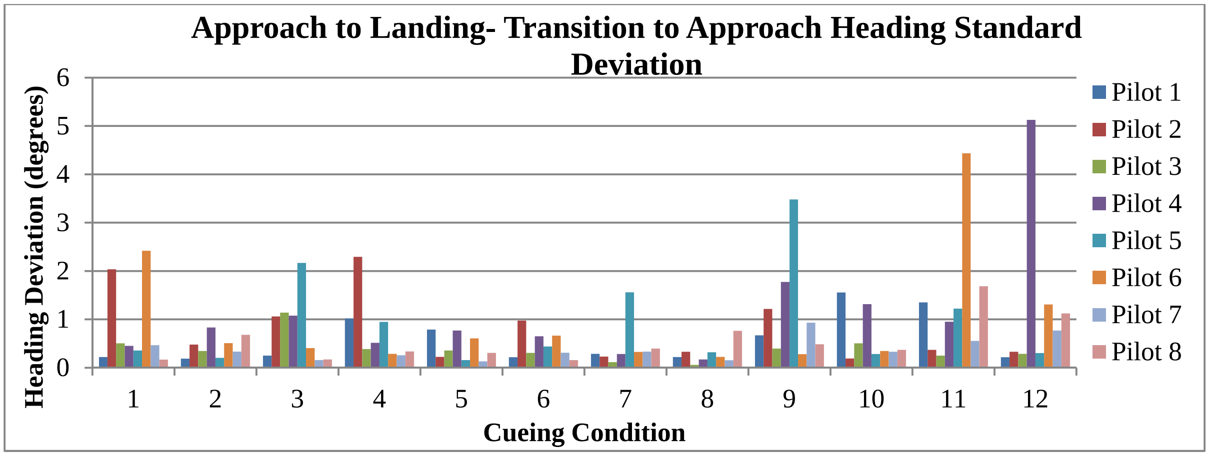


Figure C-3. Approach to Landing- Transition to Approach Heading Standard Deviation.

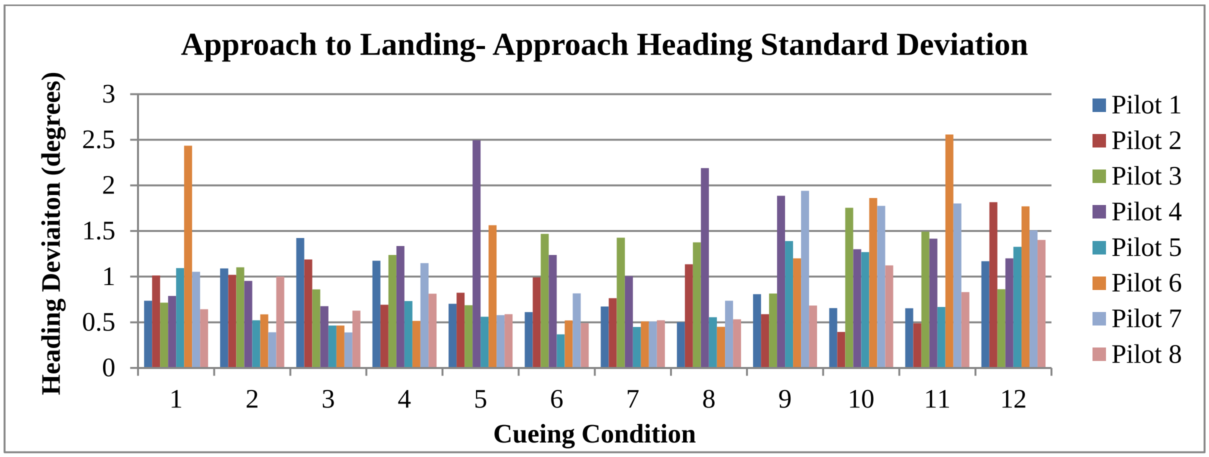


Figure C-4. Approach to Landing- Approach Heading Standard Deviation.

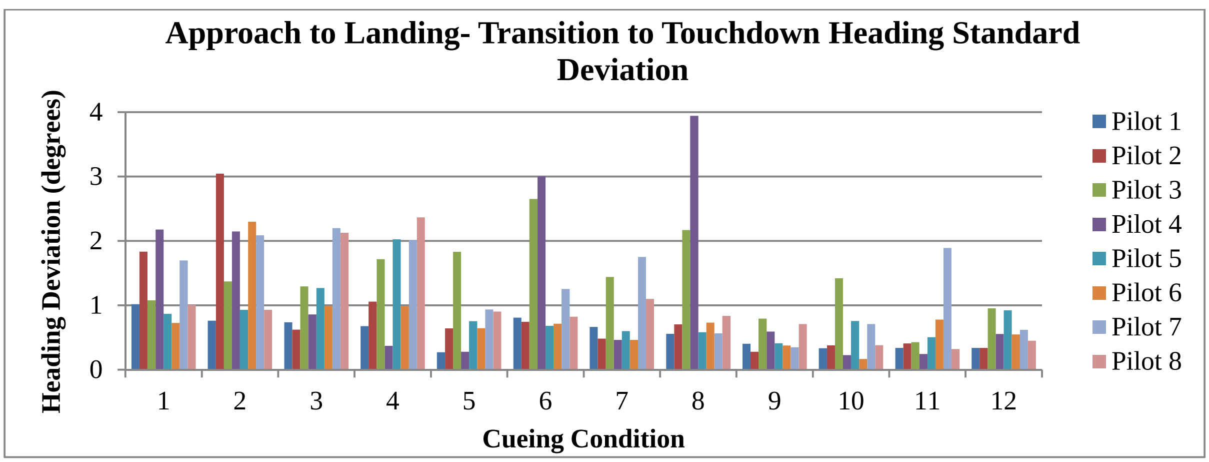


Figure C-5. Approach to Landing- Transition to Touchdown Heading Standard Deviation.

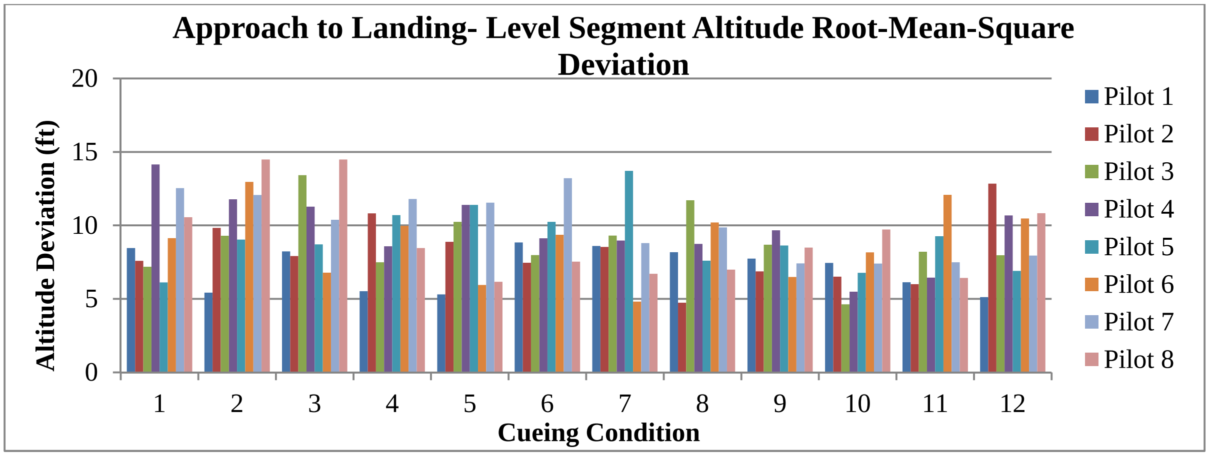


Figure C-6. Approach to Landing- Level Segment Altitude Root-Mean-Square Deviation.

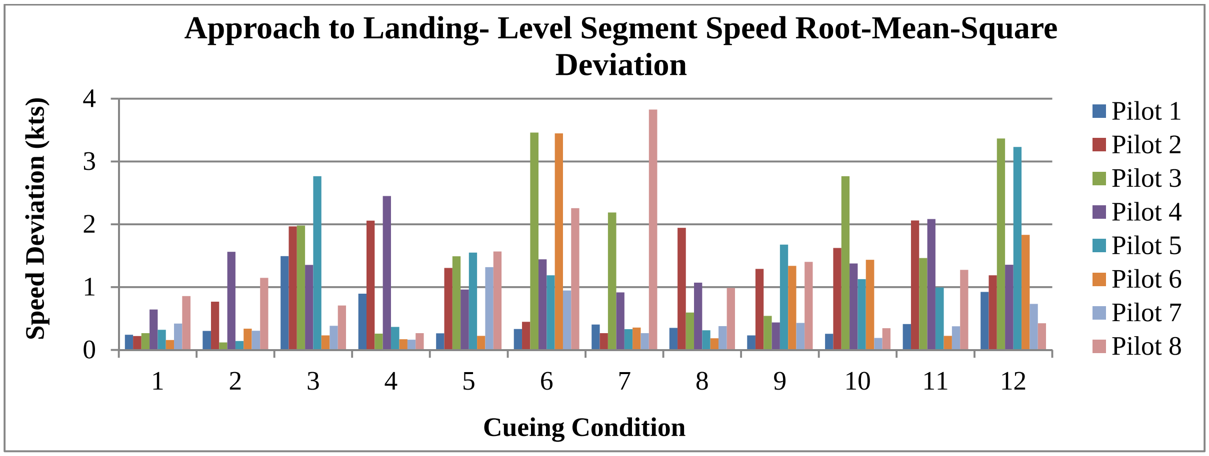


Figure C-7. Approach to Landing- Level Segment Speed Root-Mean-Square Deviation.

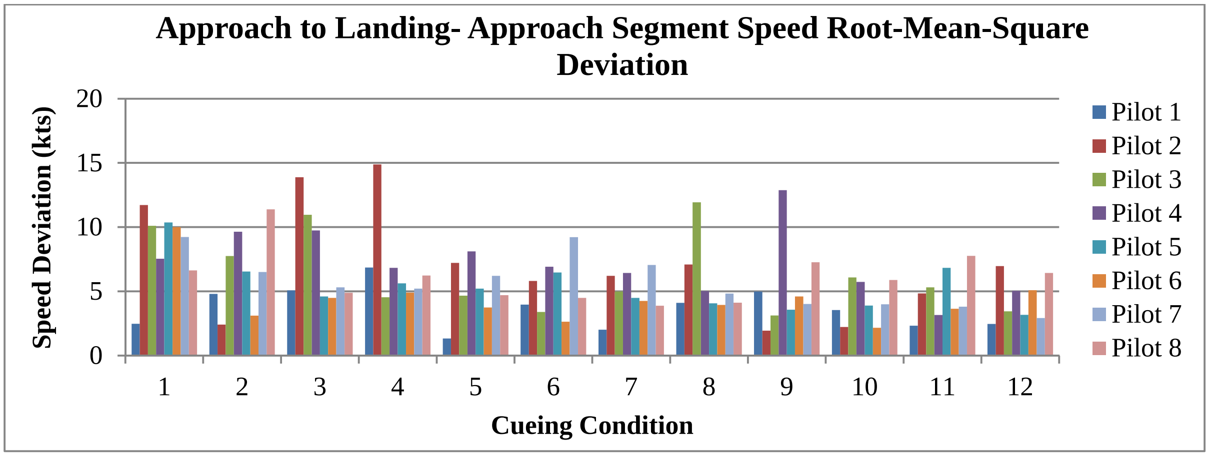


Figure C-8. Approach to Landing- Approach Segment Speed Root-Mean-Square Deviation.

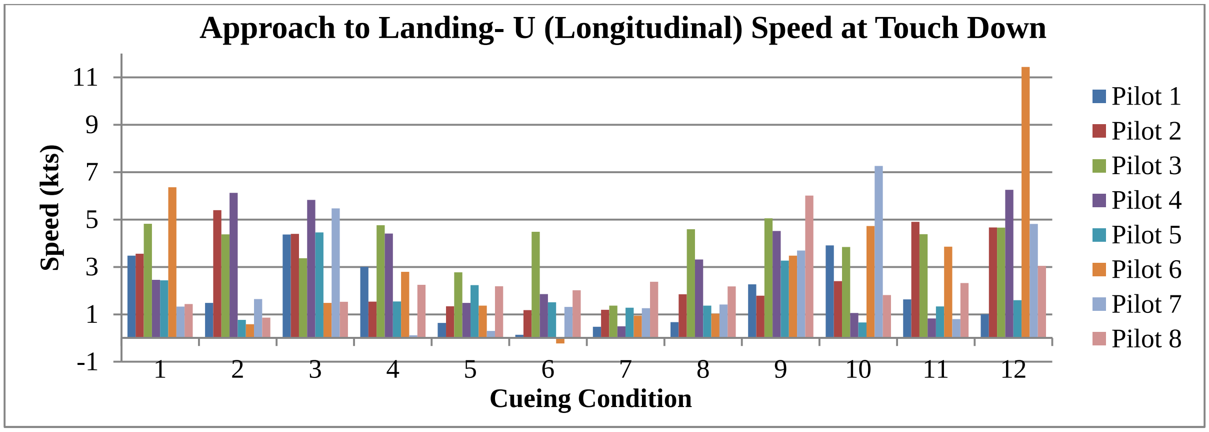


Figure C-9. Approach to Landing- U (Longitudinal) Speed at Touch Down.

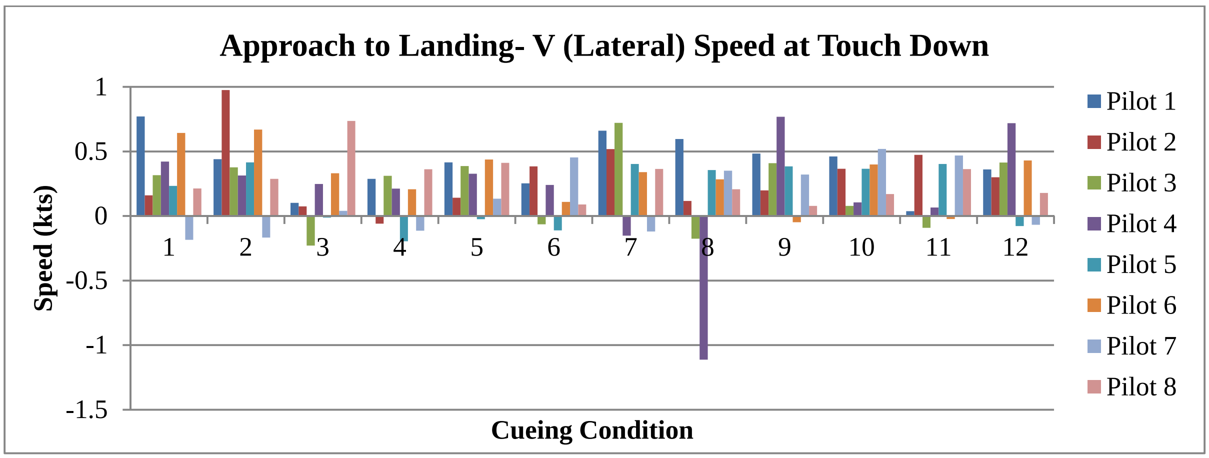


Figure C-10. Approach to Landing- V (Lateral) Speed at Touch Down.

Approach to hover

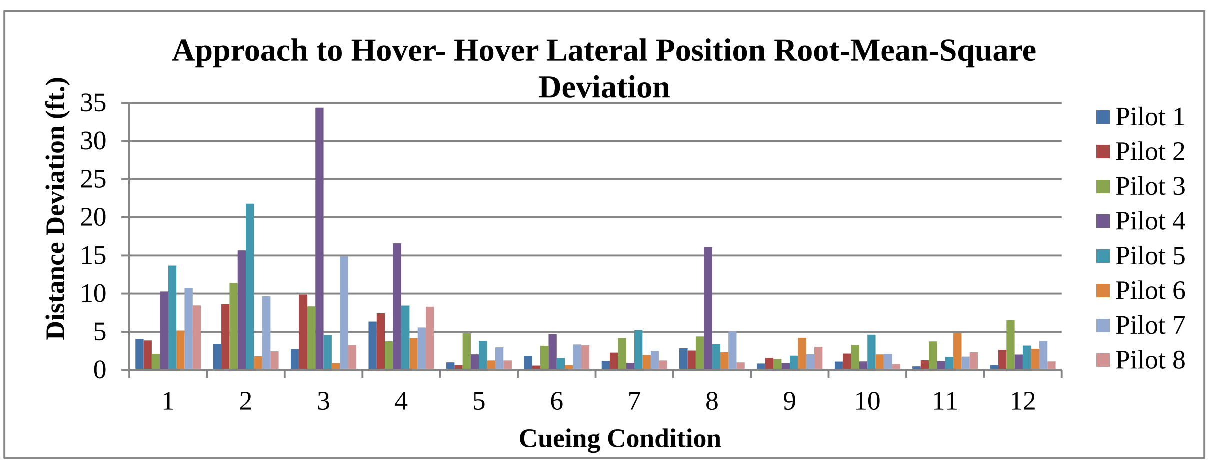


Figure C-11. Approach to Hover- Hover Lateral Position Root-Mean-Square Deviation.

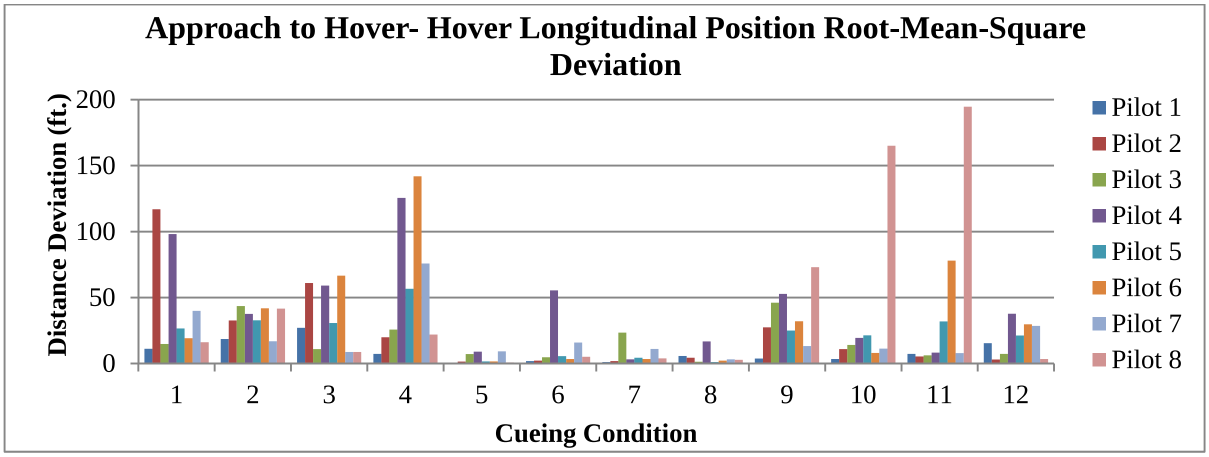


Figure C-12. Approach to Hover- Hover Longitudinal Position Root-Mean-Square Deviation.

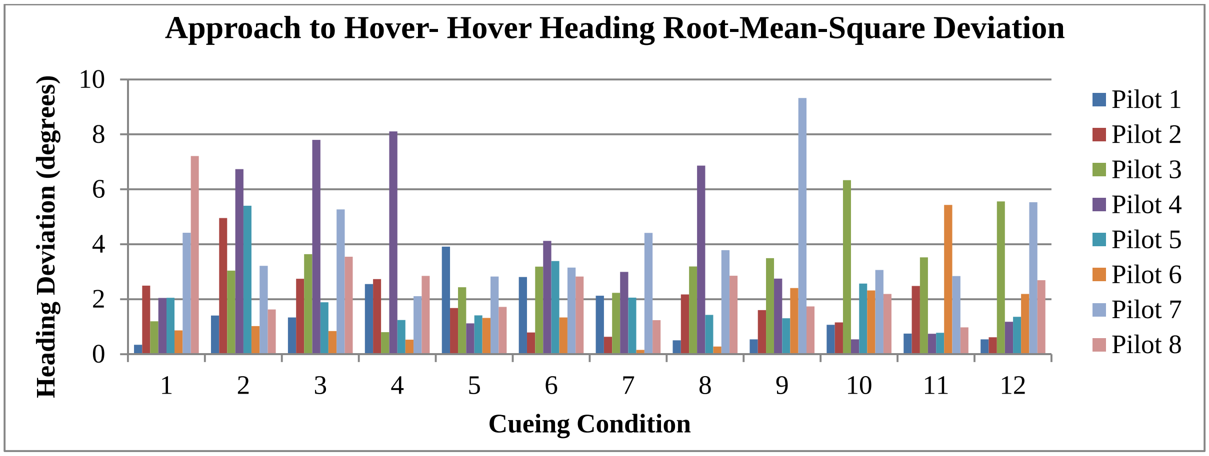


Figure C-13. Approach to Hover- Hover Heading Root-Mean-Square Deviation.

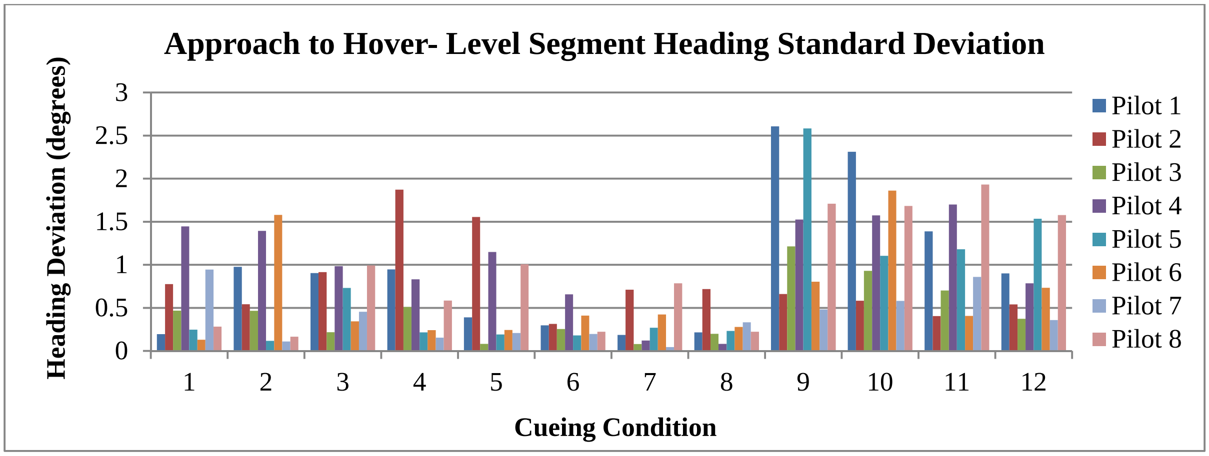


Figure C-14. Approach to Hover- Level Segment Heading Standard Deviation.

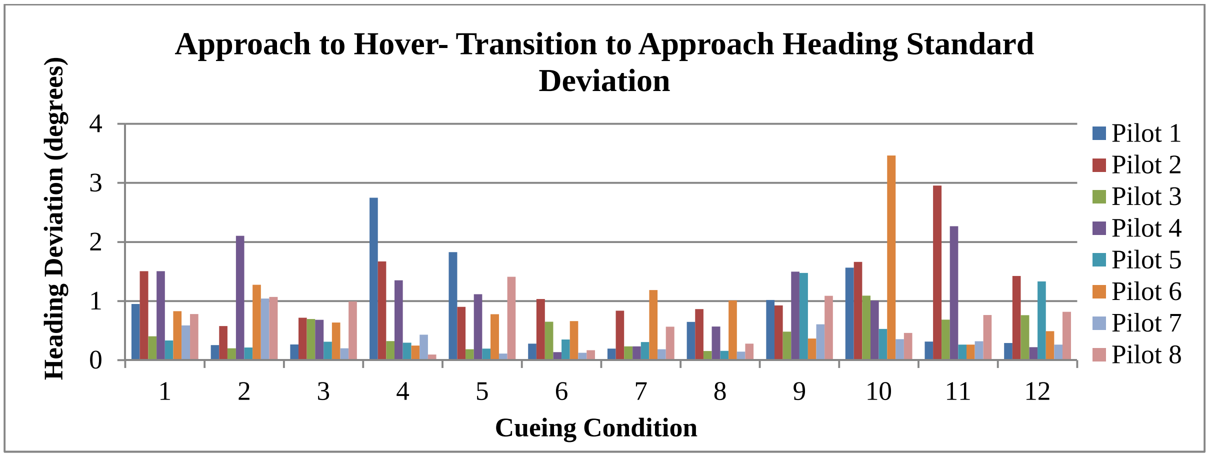


Figure C-15. Approach to Hover- Transition to Approach Heading Standard Deviation.

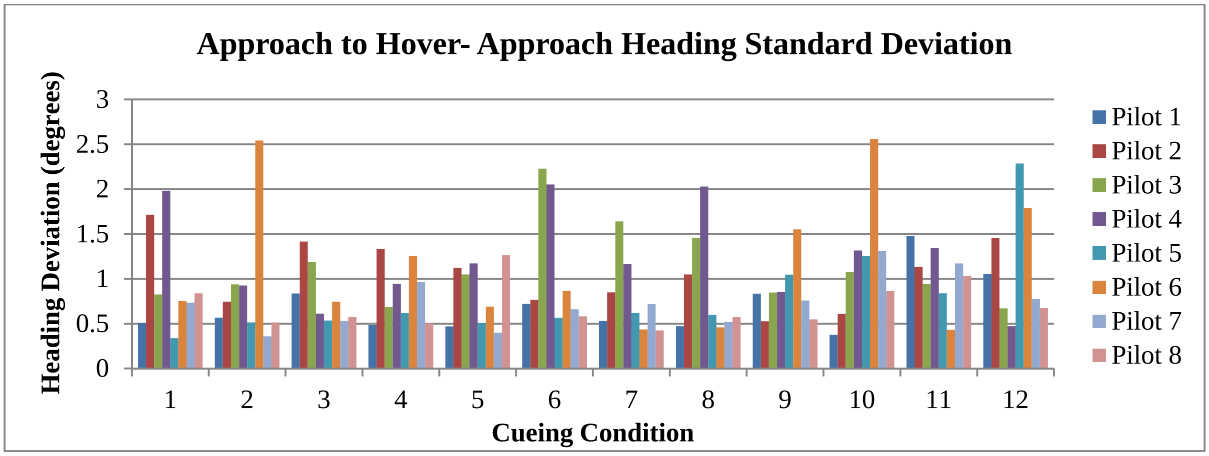


Figure C-16. Approach to Hover- Approach Heading Standard Deviation.

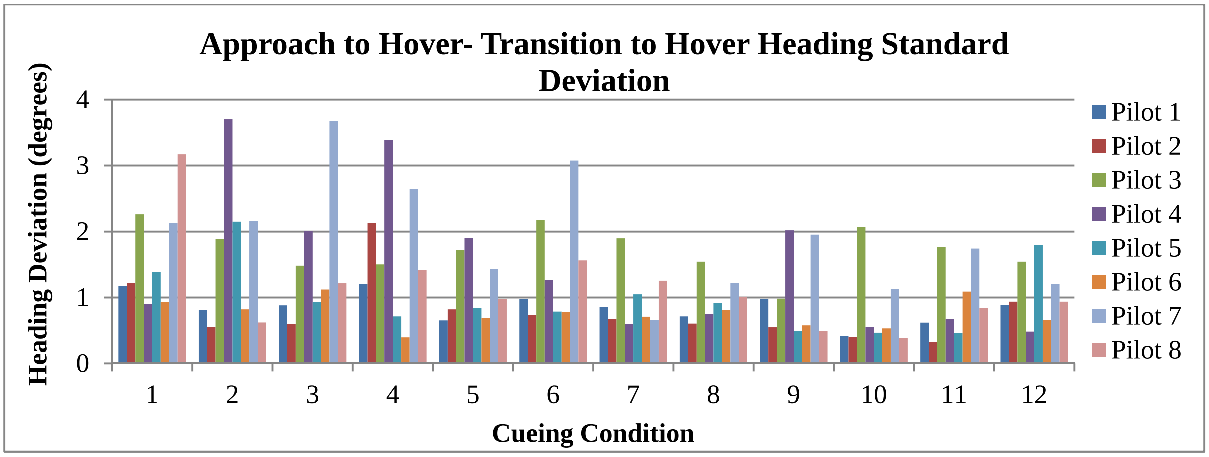


Figure C-17. Approach to Hover- Transition to Hover Heading Standard Deviation.

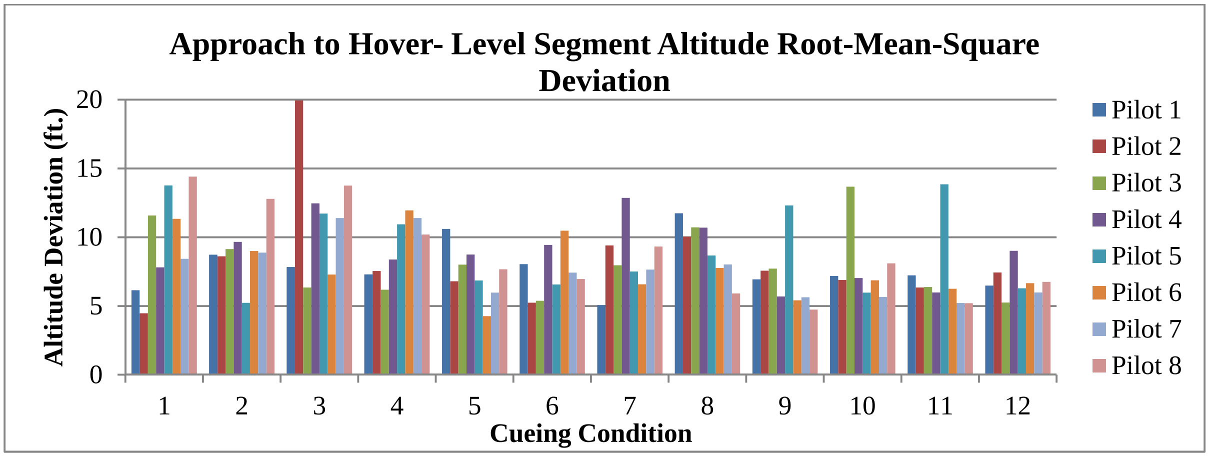


Figure C-18. Approach to Hover- Level Segment Altitude Root-Mean-Square Deviation.

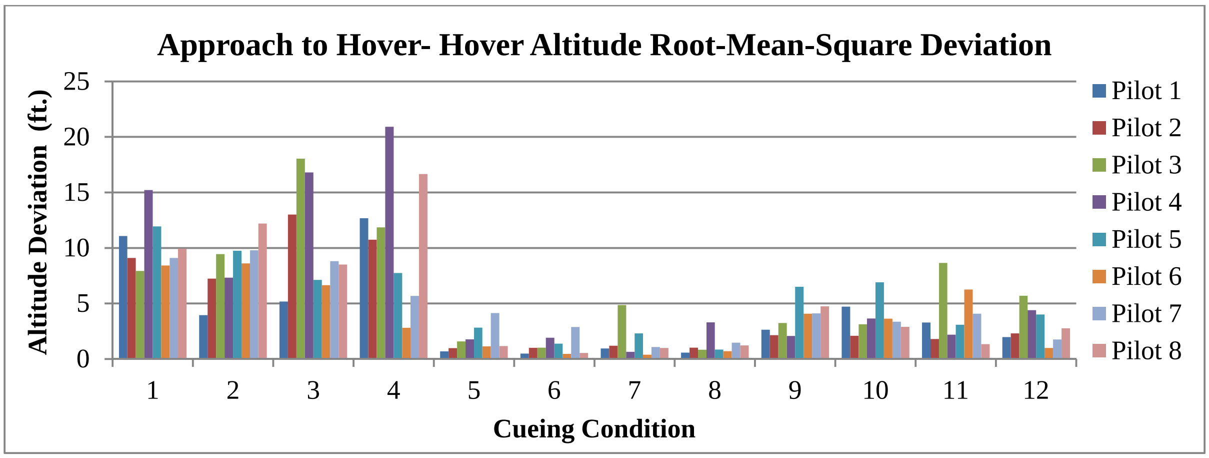


Figure C-19. Approach to Hover- Hover Altitude Root-Mean-Square Deviation.

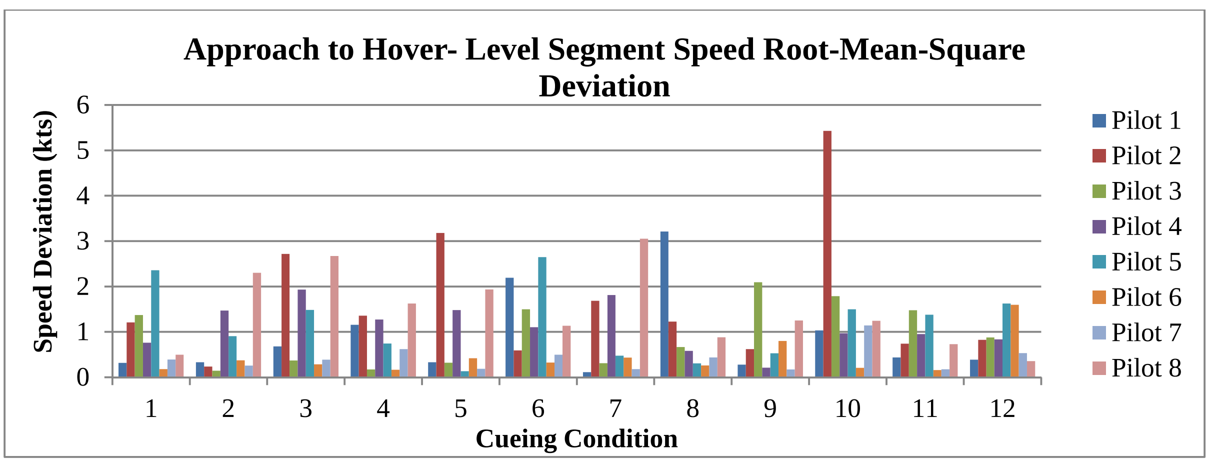


Figure C-20. Approach to Hover- Level Segment Speed Root-Mean-Square Deviation.

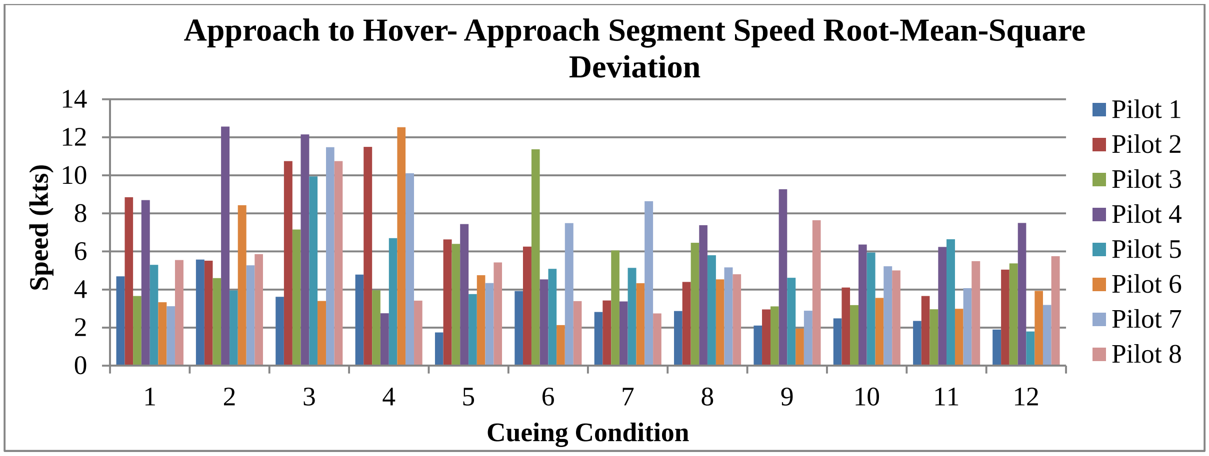


Figure C-21. Approach to Hover- Approach Segment Speed Root-Mean-Square Deviation.

Hover

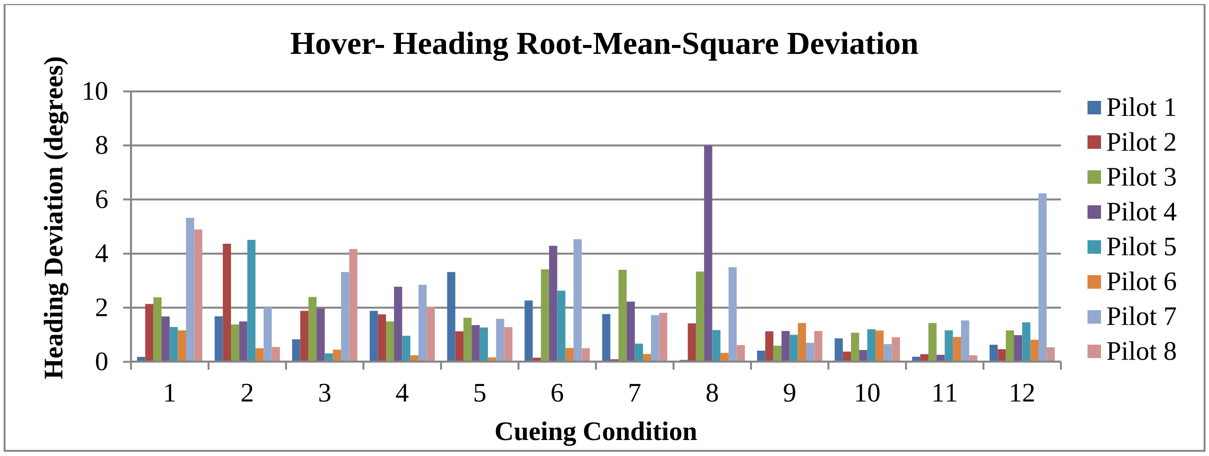


Figure C-22. Hover- Heading Root-Mean-Square Deviation.

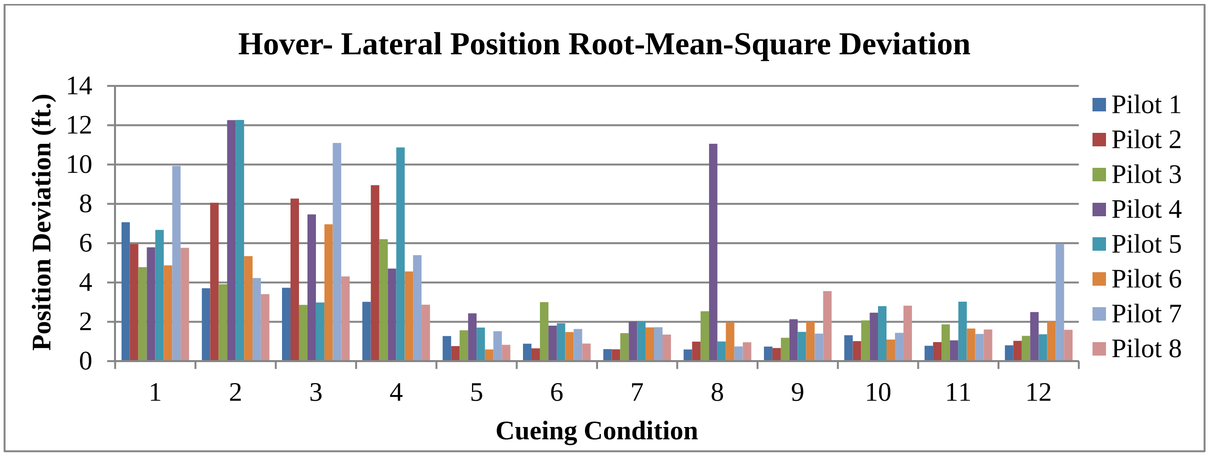


Figure C-23. Hover- Lateral Position Root-Mean-Square Deviation.

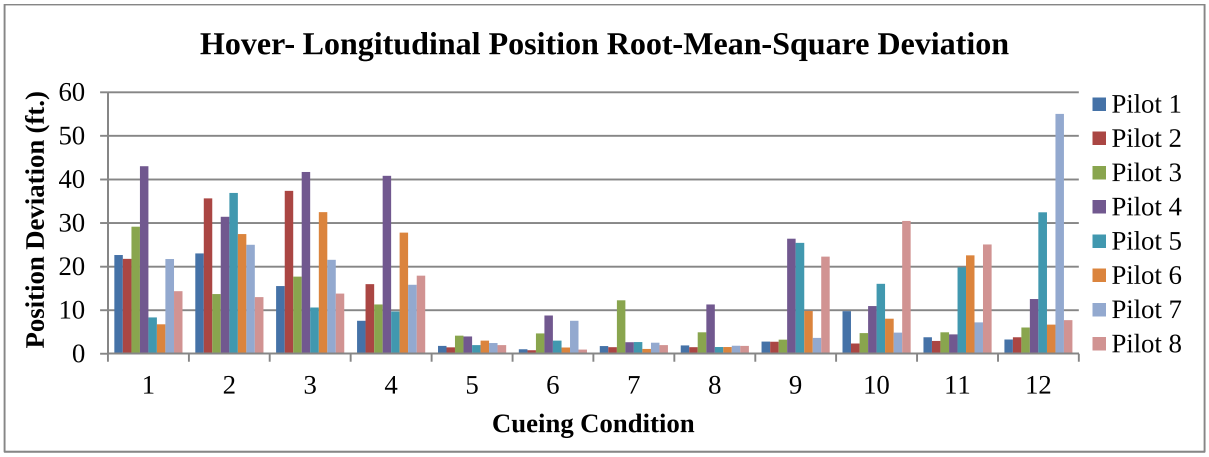


Figure C-24. Hover- Longitudinal Position Root-Mean-Square Deviation.

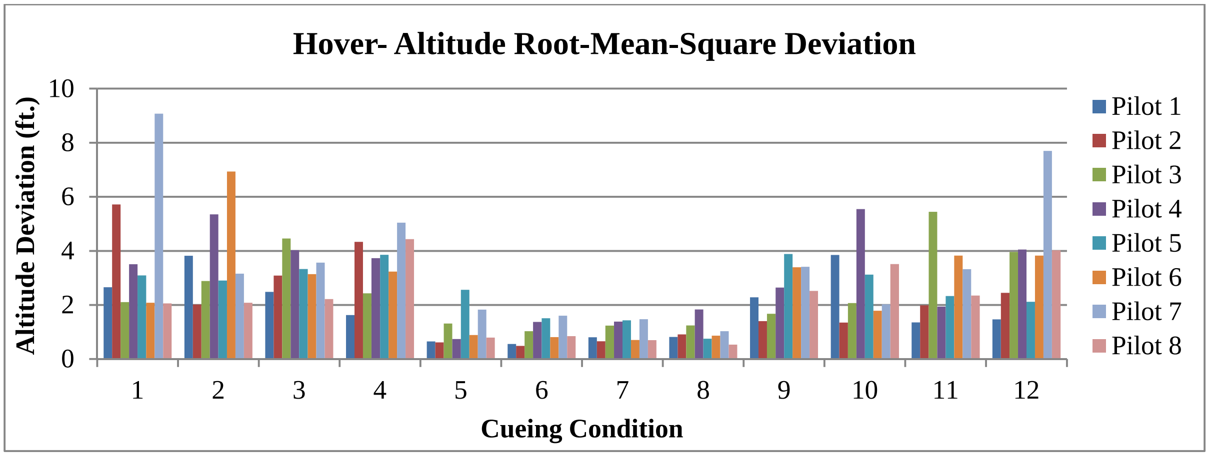


Figure C-25. Hover- Altitude Root-Mean-Square Deviation.

Sidestep

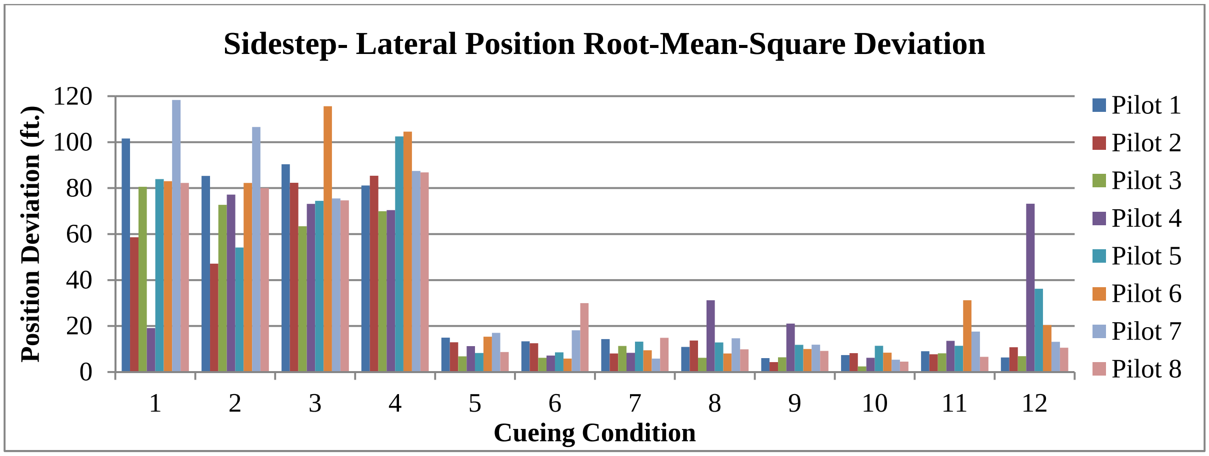


Figure C-26. Sidestep- Lateral Position Root-Mean-Square Deviation.

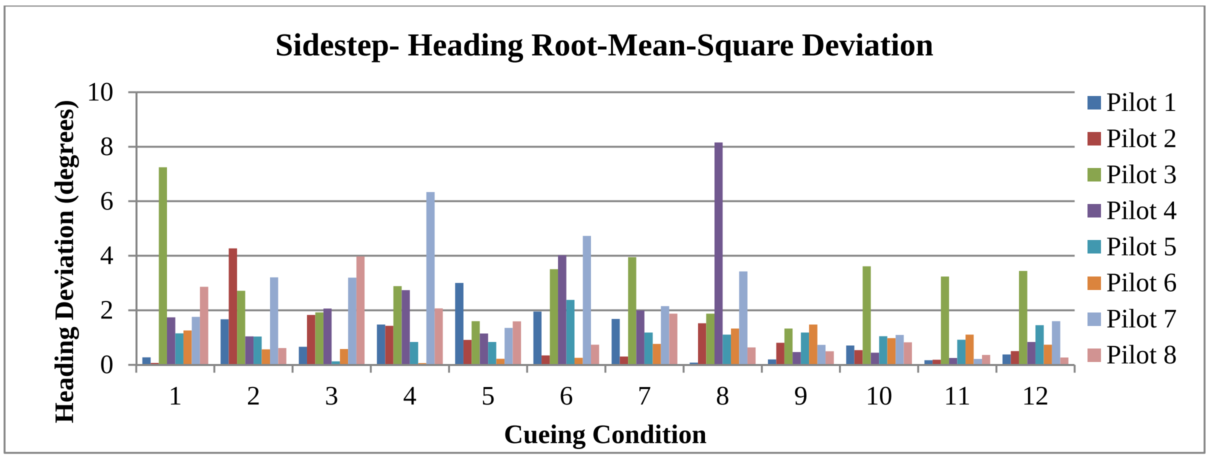


Figure C-27. Sidestep- Heading Root-Mean-Square Deviation.

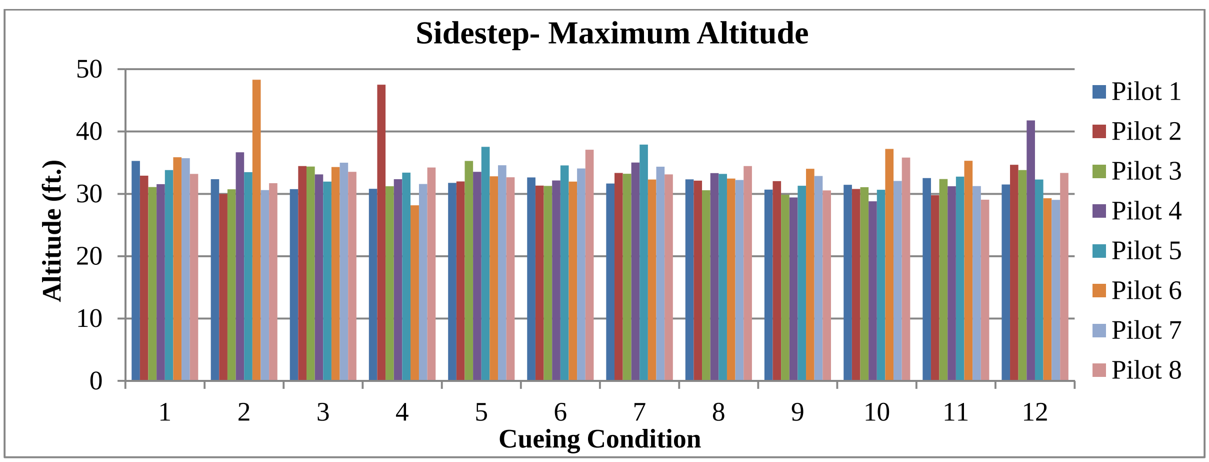


Figure C-28. Sidestep- Maximum Altitude.

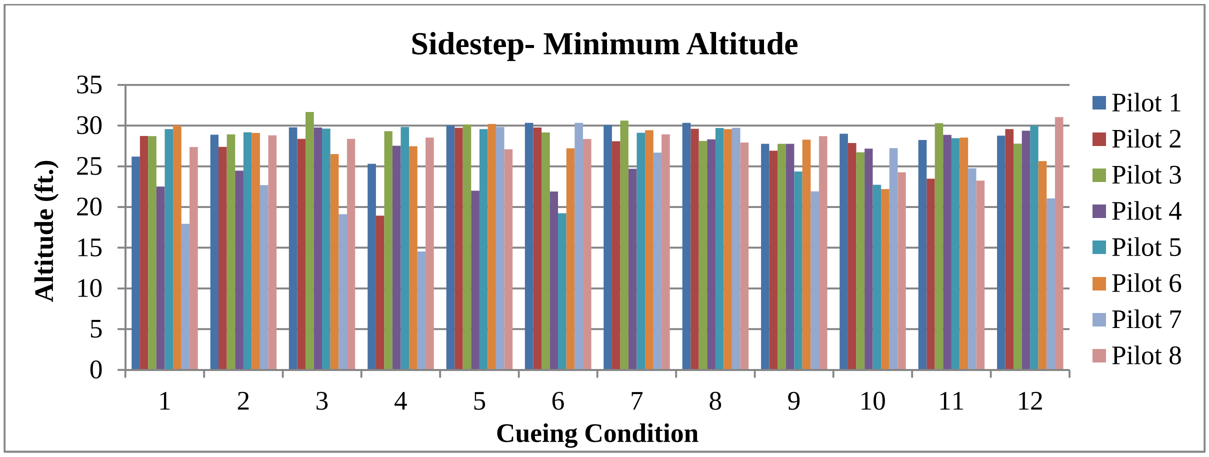


Figure C-29. Sidestep- Minimum Altitude.

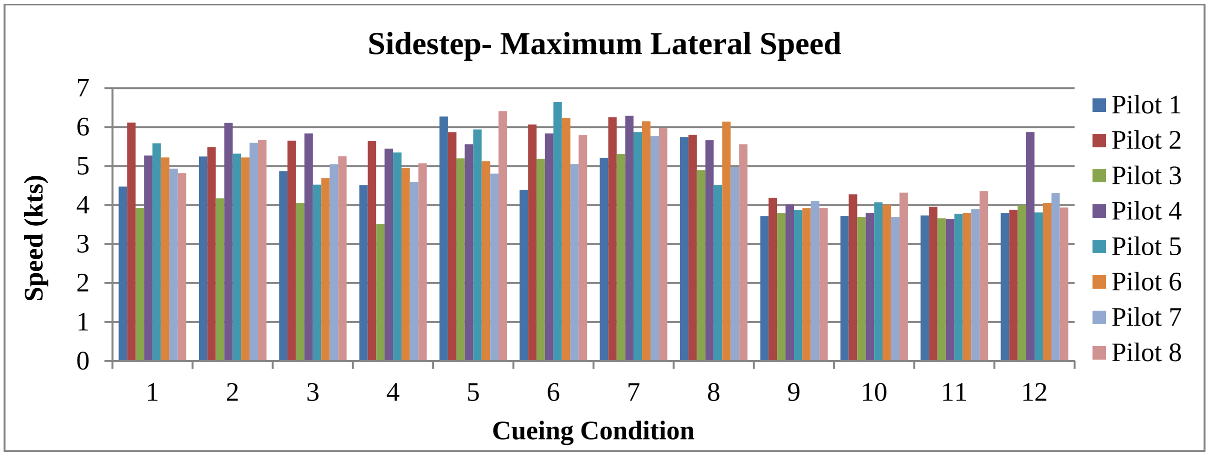


Figure C-30. Sidestep- Maximum Lateral Speed.

Appendix D.

Biometric results.

Biometric Output Means (by Measure, Condition, and Maneuver)

1) Mean Heart Rate (BPM) (by Condition and Maneuver)

	AppHOV	AppLND	HOV	Side
1	81.58143 (6.34)	83.48814 (5.99)	78.51386 (7.58)	82.03614 (8.48)
2	81.38643 (6.92)	83.75167 (6.12)	81.10533 (8.75)	81.81417 (7.06)
3	80.77800 (4.94)	82.11829 (6.58)	77.62957 (5.45)	79.69300 (4.89)
4	82.47700 (7.72)	84.62933 (4.26)	81.40467 (6.24)	80.66729 (7.91)
5	79.19300 (4.93)	80.03400 (5.35)	78.96514 (5.95)	79.50157 (4.73)
6	81.61200 (2.24)	83.03833 (4.49)	81.77329 (3.55)	82.27029 (4.44)
7	81.69800 (7.07)	84.08043 (5.99)	82.66671 (6.57)	84.45543 (8.68)
8	80.54857 (8.22)	83.60557 (6.53)	81.10929 (7.99)	85.07614 (5.66)
9	76.59514 (6.02)	81.97200 (8.49)	75.49071 (5.25)	77.03871 (5.84)
10	80.89680 (6.38)	82.90867 (6.15)	79.12060 (8.44)	82.62850 (8.03)
11	82.13900 (6.24)	81.14986 (6.94)	80.97286 (6.26)	82.89929 (5.71)
12	77.63783 (6.38)	81.11060 (6.76)	79.69514 (6.99)	79.26500 (9.53)

2) Mean Respiration Intervals (s) (by Condition and Maneuver)

	AppHOV	AppLND	HOV	Side
1	1.510000 (0.17)	1.534875 (0.16)	1.469250 (0.18)	1.463000 (0.09)
2	1.546500 (0.06)	1.590625 (0.18)	1.620750 (0.13)	1.660000 (0.09)
3	1.522625 (0.11)	1.564375 (0.13)	1.567125 (0.11)	1.486875 (0.09)
4	1.521375 (0.15)	1.548250 (0.11)	1.569000 (0.12)	1.544625 (0.09)
5	1.573750 (0.11)	1.568625 (0.09)	1.585125 (0.12)	1.574500 (0.08)
6	1.532000 (0.13)	1.551429 (0.06)	1.575625 (0.13)	1.519125 (0.14)
7	1.526625 (0.11)	1.551375 (0.11)	1.538375 (0.13)	1.541000 (0.12)
8	1.522625 (0.11)	1.524625 (0.12)	1.552125 (0.13)	1.528250 (0.14)
9	1.561625 (0.11)	1.527375 (0.11)	1.611875 (0.11)	1.581875 (0.17)
10	1.511500 (0.12)	1.488250 (0.11)	1.563000 (0.11)	1.586875 (0.14)
11	1.550875 (0.12)	1.536875 (0.13)	1.565375 (0.12)	1.612375 (0.12)
12	1.561875 (0.14)	1.502750 (0.15)	1.564500 (0.06)	1.606571 (0.09)

3) Mean Tonic GSR (mS) (by Condition and Maneuver)

	AppHOV	AppLND	HOV	Side
1	5.989375 (5.77)	5.190714 (6.64)	5.484250 (5.32)	5.464375 (5.33)
2	4.326667 (2.09)	4.931667 (1.66)	4.505000 (1.81)	4.853667 (1.74)
3	8.912000 (7.82)	7.142857 (7.01)	8.574400 (7.42)	9.282800 (7.95)
4	6.903714 (4.81)	3.540000 (2.87)	6.882429 (5.50)	6.888429 (5.67)
5	6.132250 (4.95)	6.501000 (5.38)	5.443875 (4.84)	3.716857 (3.33)
6	4.000000 (2.18)	3.338333 (2.15)	3.751667 (2.14)	2.631429 (2.16)
7	5.492833 (4.26)	4.013333 (2.53)	3.042000 (2.41)	3.732600 (2.55)
8	5.509250 (5.62)	5.896500 (5.75)	3.923750 (2.14)	4.317125 (2.41)
9	3.775571 (5.96)	2.384286 (2.34)	3.467143 (2.49)	3.235714 (2.67)
10	3.452857 (2.25)	4.668571 (1.95)	3.707143 (2.50)	3.861667 (1.83)
11	4.064714 (2.80)	3.084286 (2.43)	3.634000 (2.77)	3.943875 (3.29)
12	4.183000 (1.84)	3.813333 (2.28)	4.371500 (2.02)	4.072833 (2.41)

4) Mean Sympathetic HRV Ratio (by Condition and Maneuver)

	AppHOV	AppLND	HOV	Side
1	4.068571 (5.45)	2.558571 (2.33)	4.890000 (5.06)	1.2742857 (1.07)
2	3.975714 (4.58)	4.725000 (7.74)	3.611667 (4.89)	0.8066667 (0.68)
3	1.864286 (1.36)	1.958571 (2.36)	1.784286 (1.10)	1.1957143 (1.40)
4	5.248333 (3.51)	4.038333 (3.64)	6.408333 (11.25)	1.0814286 (1.34)
5	3.677143 (2.74)	5.290000 (6.54)	7.157143 (11.34)	1.0100000 (0.71)
6	4.734000 (6.71)	4.261667 (8.04)	2.722857 (3.13)	0.8357143 (0.65)
7	3.950000 (3.9)	2.418571 (2.18)	2.857143 (2.31)	1.3800000 (1.62)
8	4.628571 (8.78)	1.788571 (1.89)	4.577143 (5.42)	1.1400000 (1.55)
9	2.855714 (1.95)	2.340000 (1.74)	2.371429 (1.63)	0.8971429 (0.62)
10	2.898000 (4.09)	4.110000 (3.32)	6.572000 (7.11)	1.9375000 (1.28)
11	2.235714 (2.19)	3.721429 (5.51)	4.614286 (6.53)	1.2271429 (1.15)
12	1.848333 (1.69)	2.174000 (2.52)	1.734286 (1.40	1.1366667 (1.63)

5) Summary of Conditions with Lowest Biometric Stress Responses by Maneuver and Measure

	Mean HR	**Mean Resp. Int.**	**Mean GSR**	**HRV Ratio**
AppHOV	FISH+IR (9)	BOSS+IR (5)	FISH+IR+TSAS (10)	FISH+IR+TSAS+Auditory (12)
AppLND	BOSS+IR (5)	Legacy+TSAS (2)	FISH+IR (9)	BOSS+IR+TSAS+Auditory (8)
HOV	FISH+IR (9)	Legacy+TSAS (2)	BOSS+Auditory (7)	FISH+IR+TSAS+Auditory (12)
Side	FISH+IR (9)	Legacy+TSAS (2)	BOSS+TSAS (6)	Legacy+TSAS (2)

Multivariate Analysis of Variance: All Biometrics by Condition and Controlling for Maneuver Effects

($p < 0.05$)

	DF	Wilks	Approx F	Num DF	Den DF	Significance
Maneuver	3	0.14125	2.61864	12	636	0.002
Condition	11	0.40716	2.19437	44	852	<.001
Man * Cond	33	0.26453	0.45709	132	852	1.000
Residuals	213					

Summary: Even when correcting for the significant effect of Maneuver on Biometric Outcomes, there is also a significant effect for Condition. The interaction between Maneuver and Condition is nonsignificant, which suggests that the effects of the Condition were consistent across Maneuvers.

Univariate Breakdowns of Condition Effects, Controlling for Maneuver Effects

123 observations deleted due to missing data ($p < 0.05$)

Measure	DF	Sum Sq	Mean Sq	F Value	Significance
Mean HR					
Maneuver	3	225.8	75.265	1.6364	0.182
Condition	11	922.7	83.878	1.8237	0.052
Man : Cond	33	429.5	13.016	0.2830	0.999
Residuals	213	9796.7	45.994		
Mean Resp					
Maneuver	3	0.05408	0.018026	1.1227	0.301
Condition	11	0.47616	0.043287	2.9465	0.001
Man : Cond	33	0.33803	0.010243	0.6973	0.999
Residuals	213	3.12913	0.014691		
Mean GSR (Lots of missing data due to movement artifacts from hand-mounted electrodes)**					
Maneuver	3	26.3	8.778	0.4547	0.714
Condition	11	719.2	65.379	3.3865	<.001
Man : Cond	33	200.0	6.061	0.3139	0.999
Residuals	213	4112.2	19.306		
HRV Ratio					
Maneuver	3	351.9	117.302	5.2179	0.002
Condition	11	172.9	15.720	0.6993	0.739
Man : Cond	33	297.2	9.005	0.4006	0.999
Residuals	213	4788.4	22.481		

<u>Condition-Specific Effects for Each Significant Biometric Outcome Variable (Using Tukey Honestly Significant Difference Post Hoc Tests)</u>

1) <u>Mean Respiration Interval</u>

Pairwise post hoc tests of the main effect for Condition on Mean Respiration Interval (controlling for the non-significant effect of Maneuver), demonstrated the following significant pairwise differences:

Condition 2 > Condition 1 (Diff = 0.11, $p = 0.018$)

Condition 1 demonstrated a significantly lower mean inter-peak-interval for respiration than Condition 2, which suggests that pilots' stress levels were significantly lower in Condition 2 than in Condition 1.

2) <u>Mean GSR</u>

Pairwise post hoc tests of the main effect for Condition on Mean Tonic GSR (controlling for the nonsignificant effect of Maneuver), demonstrated the following significant pairwise differences:

Condition 3 > Condition 6 (Diff = 4.966, $p = 0.002$)
Condition 3 > Condition 7 (Diff = 4.251, $p = 0.028$)
Condition 3 > Condition 9 (Diff = 5.156, $p < .001$)
Condition 3 > Condition 10 (Diff = 4.454, $p = 0.008$)
Condition 3 > Condition 11 (Diff = 4.675, $p = 0.004$)
Condition 3 > Condition 12 (Diff = 4.262, $p = 0.021$)

Condition 3 demonstrated a Tonic GSR level that was significantly higher than several other Conditions, indicating that pilots' stress levels were significantly higher in this condition than Conditions 6, 7, 9, 10, 11, and 12. The differences between Condition 3 and Condition 2 (3.718) and Condition 3 and Condition 8 (3.460) were approaching significance ($p < 0.1$).

3) <u>**Mean HR was approaching significance ($p = 0.05$)</u>

Data from EKG were extremely consistent and strong, and while not as sensitive to condition shifts in an extremely small population ($N = 8$). Increased sample sizes may see significant results, and data would be among the most reliable in the biometric series. The difference between conditions that was approaching significance was between Condition 7 and Condition 9 (5.451, $p = 0.083$), which would indicate that pilots' stress levels were higher in Condition 7 than they were in Condition 9.

Maneuver-Specific Effects for Each Significant Biometric Outcome Variable

1) HRV Sympathetic: Vagal Proportion Ratio

While not sensitive to Condition effects in the present test, HRV appeared to be quite sensitive to changes between Maneuvers. Like HR, HRV data is extracted from the ECG signal, which was consistently the strongest and most accurate data collected (it was very resistant to movement artifact). HRV is divided into two proportion categories based on a spectral density analysis of frequencies; these categories are Sympathetic Activity (correlates with higher stress levels) and Vagal Activity (correlates with lower stress levels). A ratio of the proportion of variance attributed to Sympathetic Activity to the variance attributed to Vagal Activity provides a single measure of HRV: higher levels of this ratio indicate higher levels of stress.

A post hoc analysis of the significant effect for Maneuver on HRV Ratio indicated the following significant differences:

Side < HOV (Diff = 2.889, $p < .001$)
Side < AppHOV (Diff = 2.346, $p = 0.004$)
Side < AppLND (Diff = 3.908, $p = 0.016$)

The Side-Step maneuver demonstrated a significantly lower HRV Ratio than all other maneuvers, which would suggest that pilots’ stress levels were lowest while completing this maneuver.

Department of the Army
U.S. Army Aeromedical Research Laboratory
Fort Rucker, Alabama, 36362-0577
www.usaarl.army.mil

U.S. Army Medical Research and Materiel Command